

Comanche Helmet-Mounted Display Symbology Simulation: Final Report

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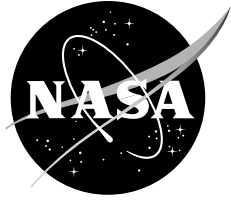
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EXECUTIVE SUMMARY

The Aeroflightdynamics Directorate (AMRDEC) conducted a simulation to examine the performance of the Comanche Contact Analog world-referenced symbology displayed on the Comanche HIDSS when compared with a compressed symbology design similar to that specified by the former MIL-STD 1295. Six experimental test pilots flew one modified ADS-33 maneuver (hover turn, bob-up), an unusual attitude recovery, and two terrain flight tactical tasks in the NASA Vertical Motion Simulator (VMS). Analysis of the pilot objective performance data and subjective data showed the following results.

Objective test results showed that 1295 symbology yielded more rapid maneuvering in the hover turn bob-up than Contact Analog symbology. The average margin of difference in the time to complete the maneuver was approximately two seconds, which was statistically significant. There were no significant differences measured between symbology sets with respect to altitude or position performance measures for all other maneuvers. The NOE target ID task data showed improved accuracy in determining heading to target when using Contact Analog over MIL-STD-1295.

Subjective test results, including handling qualities ratings (HQRs) and NASA-TLX workload ratings, showed small but consistent advantages of 1295 symbology over Contact Analog for most parameters. For the bob-up maneuver, 1295 symbology handling qualities were rated “Desired” for lateral position error and time to complete whereas Contact Analog was rated adequate. The average HQRs for all other maneuvers were rated the same for both symbology sets (see summary chart, Table 1).

Pilot comments and the results of an online questionnaire more strongly favored 1295 over Contact Analog. Repeated comments from all six pilots led to a focus on design issues with six Contact Analog symbols. Those symbols were the heading tape, horizon line, radar altitude six-second predictor, the position of the torque symbol, the absence of a hover position cue, and the widespread positioning of the symbology to the outer edges of the display field-of-view. Pilots rated the present design of three of the six symbols as having safety-of-flight implications. Those symbols were the heading tape, horizon line, and six-second predictor.

To summarize, test results showed no objective data that would warrant restricting experimental test pilots from flying constrained tasks. Small but consistent advantages were recorded for the MIL-STD-1295 symbology design when executing ADS-33 constrained tasks. No general performance differences were recorded for the operational maneuvers (NOE, contour flight modes) except for the azimuth-to-target task, which favored the Contact Analog heading tape design. There were consistent and strong pilot comments supporting the MIL-STD-1295 design over Contact Analog in both this current simulation and in Comanche Sim I. Three Contact Analog symbols warrant modification and further evaluation to mitigate safety-of-flight implications noted by participating test pilots.

A plan for symbology redesign and testing was developed. However, the Comanche program was cancelled by Department of Army in February 2004.

SECTION 1. SIMULATION TEST PLAN

1.1 Simulation Objectives

The primary purpose of this piloted simulation was to evaluate the effectiveness of two Helmet-Mounted Display (HMD) symbology sets. Those were the RAH-66 Contact Analog symbology, and a more traditional MIL-STD-1295 (ref. 7)-based design. A secondary purpose was to explore three Contact Analog-based hybrid designs. Each symbology set was examined while pilots executed one handling qualities task, a situational awareness task, and a mission-oriented scenario in the NASA Vertical Motion Simulator (VMS). Emphasis was on quantifying pilot performance, workload, and overall effectiveness of the heading tape, attitude, altitude, and hover symbology. This simulation was built upon a prior year 2002 experiment conducted in the VMS (fixed-base) with similar objectives (ref. 11, AHS 2002 paper). Significant differences from the prior simulation included: a) Use of the VMS large amplitude motion cueing; b) Use of the Automatic Flight Control System (AFCS) as the primary flight control mode throughout; c) Evaluation of hybrid Contact Analog symbology sets; d) Inclusion of unusual attitude recovery and mission-oriented terrain flight pilotage tasks.

1.2 Background

The RAH-66 Comanche Scout/Attack Helicopter was slated to be the first Army helicopter to use an HMD as the primary flight display (PFD). The symbology design concept described in the Pilot Vehicle Interface Mechanization Specification (PVIMS) (ref. 3) incorporates an inertially referenced system known as “Contact Analog,” wherein symbols appear to overlay the real-world objects they represent. Sikorsky has described the Contact Analog design philosophy as maintaining a “Gestalt,” where visual, vestibular, and proprioceptive cues remain in agreement. That is, in the virtual world of the HMD, symbols behave like the real-world parameter they represent. Earth-referenced symbols appear to remain fixed to their referents outside of the aircraft. Aircraft-referenced symbols appear to move with the aircraft. Head-referenced symbols appear to move with the head. Sikorsky symbology designers believe that decoupling any of these inputs from each other has potential for disorientation. Contact Analog symbology is based on the notion of fidelity to movement, behavior, and interrelationships of real-world referents. Dynamics, location, and behavior of a symbol represent its corresponding source of information in contact (visual) flight.

The Helmet Integrated Display Sight System (HIDSS) has recently been introduced into the Comanche flight test program. Initial tests of the primary flight symbology were flown by Army pilots in the Sikorsky Engineering Development Simulator (EDS) and in the Comanche Portable Cockpit (CPC) using a surrogate HMD prior to introducing the HMD to the flight test vehicle. These initial tests surfaced issues regarding the usability of the HMD primary flight symbology. These concerns were documented in a White Paper published by the TRADOC Systems Manager (TSM), Comanche, in August of 2001 (ref. 5, TSM White Paper). The issues were related primarily to the implementation of the heading tape and artificial horizon line, although other symbols were identified with a lesser degree of concern.

A fixed-based simulation was conducted at Ames Research Center in January–February 2002 to address the TSM's concerns. The primary objective of this effort was to examine the functionality of the Contact Analog heading tape when compared to a traditional HMD presentation designed around the former MIL-STD-1295, Human Factors Engineering Design Criteria for Helicopter Cockpit Electro-Optical Display Symbolology. Six pilots (3 Apache rated) flew four test maneuvers. There were two hover tasks, and two up-and-away tasks. Three of the four maneuvers were modified Aeronautical Design Standard 33 (ADS-33) (ref. 1) tasks and the fourth was selected from the Army Aircrew Training Manual (ATM) (ref. 4). Two flight control modes were flown as independent variables. The modes were Velocity Stabilization (VelStab) and the Automatic Flight Control System (AFCS) mode.

The 2002 simulation results validated many of the TSM's concerns. Data showed small but statistically significant improved pilot performance using MIL-STD-1295 symbology over Contact Analog. Larger performance differences were noted between flight control modes with VelStab outperforming AFCS. NASA-TLX results showed a lower workload for MIL-STD-1295 symbology over Contact Analog in both flight control modes. Readability of the Contact Analog heading tape during rapid turning movements was an issue. Handling qualities ratings indicated a need for improvement associated with the design and implementation of selected Contact Analog symbology. One conclusion of this study was that additional simulation experiments should be conducted to examine the Contact Analog symbology design in a more mission-oriented, operational setting. The results of this simulation were presented at the 58th Annual American Helicopter Society (AHS) Forum, June 2002 (ref. 11). The simulation described below is a follow-on to the 2002 simulation effort.

1.3 Simulation Overview

The Aeroflightdynamics Directorate (AFDD) conducted this experiment in the VMS driven by a high-fidelity Comanche helicopter math model integrated with a head-tracked HMD. The simulation results were to be used as an independent data source for the Aviation and Missile Research and Development Engineering Center (AMRDEC) Comanche airworthiness evaluations. The primary focus of the simulation was to collect and analyze performance data and to isolate issues regarding readability, usability, and pilot performance using the Contact Analog HMD symbology as a primary flight reference.

The experiment used a MIL-STD-1295-based symbology design and functionality as the baseline. Contact Analog functionality and performance was compared to the baseline. The simulation involved one constrained ADS-33 task, one situational awareness task, and two tactical tasks. This simulation examined the “Contact Analog” design philosophy to determine if stated benefits could be utilized without adversely affecting crew performance. The simulation attempted to quantify the issues with performance data from various performance measurement tools. Quantitative data collected were supplemented with handling-qualities ratings and pilot comments as well as situational awareness ratings.

1.4 Hybrid Symbology Sets

There were three Contact Analog-based alternate designs developed and tested that represented hybrids (mixtures) of Contact Analog and MIL-STD-1295 symbology. These hybrids were developed based on findings from the previous 2002 Comanche symbology simulation, that suggested a hybrid of the two symbology sets may improve pilot performance. The hybrid designs were strongly influenced by pilot comments from that simulation and by designs that were being informally considered by the user community at Ft. Rucker. Although the three hybrid symbology designs were compared to the baseline, this analysis was considered as a separate science and technology effort and not as a part of the primary test matrix.

1.5 Method

1.5.1 Participants

Six experimental test pilots were used as subjects to support the experiment. Four were from the Aviation Technical Test Center (ATTC) and two were local Army and NASA pilots. Pilots had flight experience in multiple airframes, each logging an average 3511.83 total flight hours ($n = 6$) (fig. 1). The low-time pilot had over 2000 flight hours. All pilots were instrument rated. Five of six pilots were night vision goggle qualified. Pilot selection criteria required pilots with minimal exposure to MIL-STD 1295 symbology in order to minimize any bias for 1295 over Contact Analog symbology. Consequently, few pilots reported prior HMD experience. Five of the six pilots had the UH-60 designated as their primary aircraft and one had CH-47 as primary.

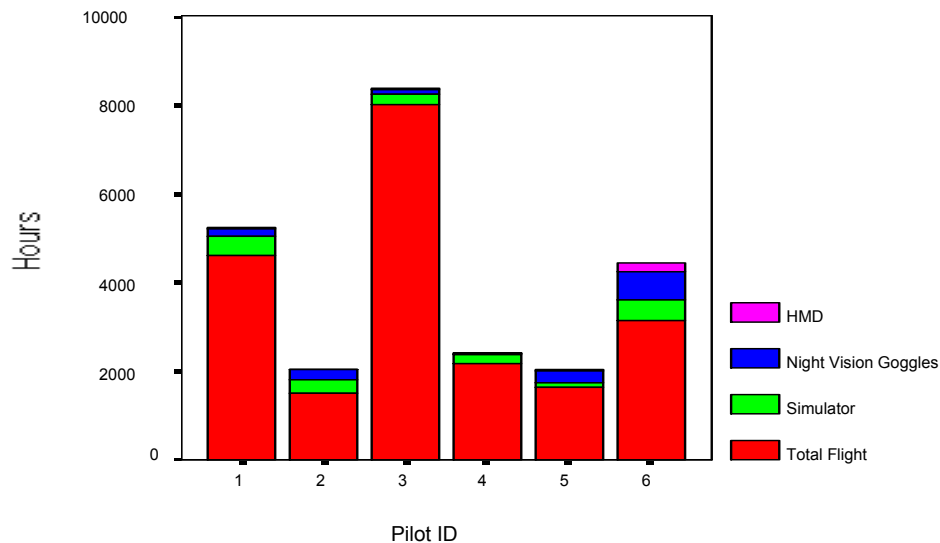


Figure 1. Summary of Test Pilot Flight Experience.

1.6 Experimental Design

A 2 x 2 x 4 (symbology x block x trial) factorial, within-subjects experiment with repeated measures was conducted. Symbology was tested across two levels: Contact Analog and compressed. Symbology conditions were blocked with counterbalanced presentation, such that pilots completed all maneuvers in one symbology set before training and testing in a different symbology. Maneuvers were blocked with counterbalanced presentation, such that all maneuvers were completed once before a block repetition. Four repetitions of each maneuver were executed within a single block. In sum, pilots completed 8 hover turn bob-ups (BU), 8 unusual-attitude recoveries (UA), and 2 tactical missions (TM) in each of the symbologies (fig. 2).

BLOCK 1			BLOCK 2		
task 1	task 2	task 3	task 1	task 2	task 3
BU x 4	UA x 4	TM	BU x 4	UA x 4	TM

Figure 2. Test Matrix (repeated for Alternate Symbology Set).

Tactical missions contained 2 flight profiles: contour and NOE. Contour flight always preceded NOE. Both contour and NOE flight segments were completed once per block in each symbology condition (2 total). Contour flight mode consisted of two commanded airspeed changes (increase, decrease) and two commanded altitude changes (ascend, descend). RMSE on the non-commanded parameter was calculated in order to test a hypothesis on incorrect control inputs due to placement of airspeed and altitude symbology. Time to complete the command was also measured.

NOE flightpaths consisted of an equal number of waypoints ($n = 4$) with two targets located within 40-deg FOV and two targets outside, for a total of 4 targets per flight. Time between target detection and pilot annunciation (azimuth to target) was recorded. Accuracy of pilot annunciation of azimuth to target was analyzed.

The dependent measures varied by maneuver and correlated with parameters outlined in ADS-33. Separate 2 x 2 x 4 (symbology x block x repetition) analyses of variance (ANOVAs) were conducted by maneuver and parameter. For the tactical missions, contour and NOE data were analyzed separately. Subjective dependent measures collected were NASA-TLX ratings (Hart & Staveland, 1988), measuring perceived workload and situational awareness, and aircraft handling-quality ratings (Cooper & Harper, 1969) (ref. 10) for hover bob-up maneuvers only. Additional subjective ratings on specific display items (i.e., horizon line reference) within a symbology set were also collected. Ratings given assessed the usefulness of the display item and ease or difficulty to control related aircraft axes.

Finally, 3 hybrid symbologies were presented to the pilots at the end of the primary experiment to collect additional data. Pilots executed a hover turn bob-up maneuver in each hybrid condition. Symbologies were presented in counterbalanced order. Four repetitions were completed in each symbology with initiated turn direction counterbalanced (left, right or right, left). In total, data from 12 hover turn bob-up maneuvers were collected. Means and standard deviations of the data were calculated for the maneuver from the tolerance parameters provided.

1.7 Simulation Design

1.7.1 Flight Control System Models

The Comanche core Primary Flight Control System (PFCS), mission PFCS, and the Automatic Flight Control System (AFCS) were primarily used in this simulation. The hover bob-up maneuver, however, was flown in both AFCS and Velocity Stabilization (VelStab) with the Position Hold selectable mode engaged. Altitude Hold was not used. The intent was to contrast the workload differences in maintaining hover position in AFCS mode only when compared with Position Hold engaged. The choice to fly the majority of the experiment in AFCS was based on the desire to place more emphasis on the "hand flying" aspect of the available flight control systems. The results of Comanche Simulation I in 2002 indicated AFCS to be the most demanding flight mode on pilot performance and produced the most significant test results.

The Comanche math models were loaded on the VMS host computer. The flight control system software used in the prior Comanche VMS simulation was used for this experiment. The software for the flight control system had been supplied and checked out by Boeing engineers to support Comanche Sim I. It was based on Operational Flight Program (OFP) 2D. As of April 03, OFP 2E was presently in flight test. Boeing engineers stated there were no changes from 2D to 2E that would impact the HMD symbology study. A validation test card was developed that specified specific maneuvers and procedures be flown that would ensure the vehicle math model, flight control system software, and the symbology performed in accordance with dynamic check cases and the performance parameters documented in the PVIMS. The Comanche Sim II project pilot flew this test card both in fixed-base and on full motion in the VMS F-Cab to validate the flight control system and symbology performance. An independent validation was also performed, which is described later in this report.

1.7.2 Symbology Sets

The Comanche Contact Analog PFD symbology graphic display and the associated drivers were identical to Comanche Sim I. The MIL-STD-1295 symbology and drivers from the previous simulation were also repeated in this simulation. The 1295 symbology was driven using the Comanche drive-laws to remain compatible with the Comanche flight control system. The symbology drivers were linked with the Comanche math model and control system models as required for data exchange. In addition to the above, the SimLab support staff developed three hybrid Contact Analog symbol sets. One incorporated the standard Contact Analog heading tape, which was screen-fixed in the roll axis, but remained referenced to the pilot's head movement as well as aircraft heading. The second hybrid incorporated a screen-fixed, compressed MIL-STD-1295 heading tape that was not head-referenced. The third hybrid was the standard Contact Analog symbology set with modified drive laws for the radar altimeter six-second predictor symbol. No weapons, tactical situation, or systems management symbology was displayed for this simulation. The symbology was displayed on a Kaiser ProView 50 HMD supplied by the Comanche PM from the Comanche Portable Cockpit. The Comanche Test Team used the procedures developed during the prior simulation to check out the symbology and drivers during simulation development.

1.7.3 Symbology Description

Figures 3 and 4 present both graphics and a short narrative description of the Contact Analog symbology design.

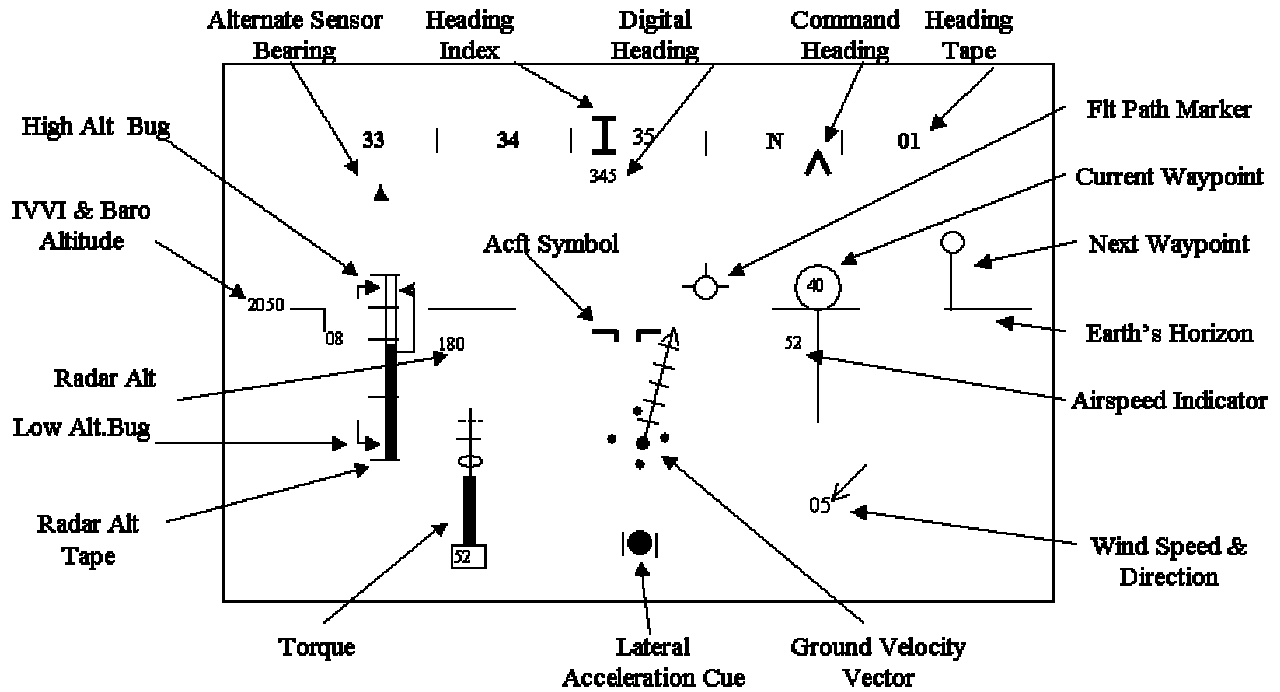


Figure 3. Contact Analog Symbol Set.

1.7.4 Contact Analog Heading Tape Description

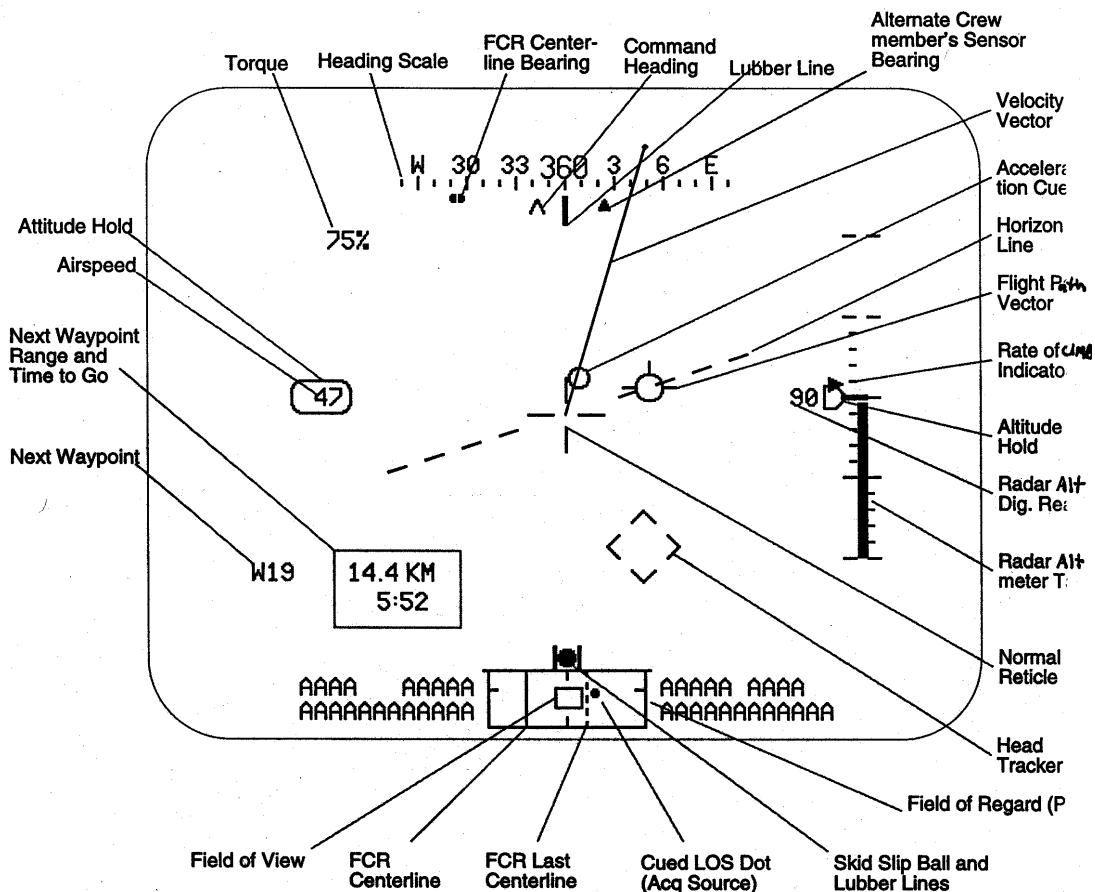
The Contact Analog implementation of the heading tape is illustrated below. Key features of the symbology are described in bullet form. The reference for the description is the Pilot Vehicle Interface Mechanization Specification (PVIMS) for Comanche (Rev. F, 7/99).



Figure 4. Contact Analog Heading Tape.

- The HMD heading tape symbol is earth-stabilized in roll and azimuth, screen-stabilized in elevation, and moves across the display in relation to changes in heading of the aircraft and the pilot's head.
- The heading tape remains aligned with the real-world horizon.
- When the A/C is flying straight and level, the heading tape appears to the pilot as a continuous 360° tape around the aircraft. As an example, if the aircraft is heading due north and the pilot looks 90° to the right, "E" appears at the center of the heading tape. Approximately 40° remain in the instantaneous field of view (FOV).

- The heading tape has numerals at 10° increments (i.e., 10°, 20°, 30°, etc.) and has hash marks at 5° increments in between (i.e., 5°, 15°, 25°, etc.). Alphanumeric characters (N, S, E, W) are displayed at the cardinal headings. The heading tape is removed in the de-clutter mode.
- The heading is referenced to Magnetic North.
- The A/C heading reference appears as an I-Bar that is earth-stabilized in roll, screen-stabilized in elevation, and aircraft-stabilized in azimuth. The steering cue symbol (upward-pointing caret) is stabilized like the I-Bar symbol and indicates commanded heading (desired heading to next waypoint) and moves horizontally across the display below the heading tape.
- Aircraft heading is displayed digitally in the top center of the HMD display beneath the heading tape and is screen-fixed in that location. The digital readout is boxed when heading hold is engaged.
- The artificial horizon line has occlusion priority over the heading tape when the head is tipped down enough to bring the two symbols into proximity.



1.7.5 Compressed Heading Tape Description



Figure 6. Compressed Heading Tape.

- The heading tape is screen-fixed and displayed at the top area of the HMD. Screen- fixed means it appears as if painted on the helmet visor and moves with the pilot's head.
- It is an analog moving scale that presents magnetic heading with a total range of 360°. A total of 180° are in the instantaneous FOV at all times.
- The scale is incremented every 10° and the major cardinal headings are alphanumerically labeled.

Figures 7 and 8 present both graphics and a short narrative description of the hybrid symbology designs.

1.7.6 Hybrid 1 Symbology Set Description

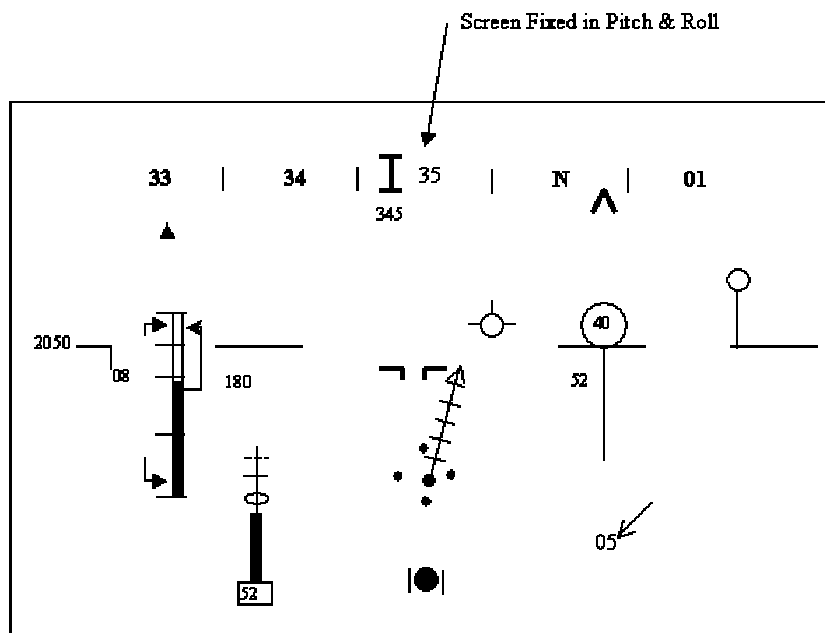


Figure 7. Hybrid 1 Symbology.

- Standard Contact Analog symbology set with heading tape modified to be screen-fixed in pitch and roll axis
- Remains head-tracked and aircraft-tracked in the yaw axis

1.7.7 Hybrid 2 Symbolology Set Description

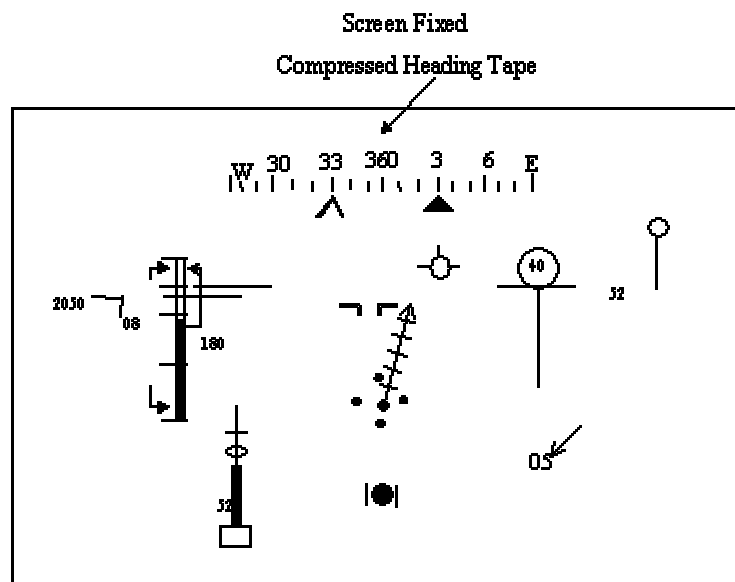


Figure 8. Hybrid 2 Symbolology.

- Compressed heading tape replaces Contact Analog heading tape
- Tape is screen-fixed in roll and pitch axis (gyro-stabilized, not true earth referenced)
- Appears as if painted on the helmet visor

1.7.8 Hybrid 3 Symbolology Set Description

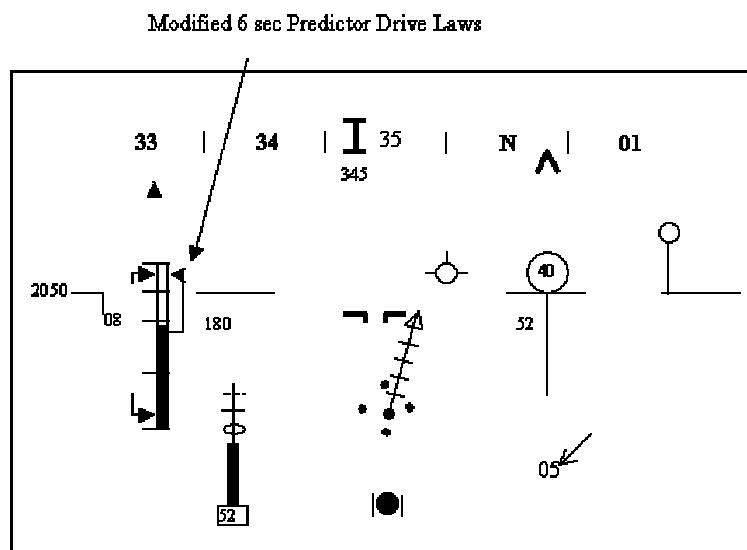


Figure 9. Hybrid 3 Symbolology.

- Standard Contact Analog symbology (fig. 9)
- Modified 6-second predictor drive laws

1.8 Simulation CAB and Hardware

The simulation utilized the VMS F-CAB as the cockpit. It was initially set up in the fixed-base lab of the VMS facility for checkout purposes before being moved onto the motion-based beam. The cockpit was configured for a single pilot with a sidearm controller and collective (fig. 10). A helmet mounted display and head-tracker provided the primary flight information to the pilot. A single panel-mounted Horizontal Situation Display (HSD) with a moving map was installed. The set-up was not intended to be a duplication of the Comanche cockpit. This austere arrangement provided only the controls and displays necessary to conduct the simulation. A detailed description of the controls and displays follow.



Figure 10. General Cockpit Arrangement.

1.8.1 Controllers

A four-axis SAC provided longitudinal and lateral cyclic control, yaw axis control, and limited heave control. This controller (fig. 11) was loaned from the Comanche Portable Cockpit (CPC) and was a full emulation of the Comanche SAC, but designed for simulator use only.

An Apache collective control was used in the simulation (fig. 12). Although it was not a Comanche collective stick, the functionality was matched as closely as possible to the Comanche. The collective was back-driven and had a displacement matching the Comanche specification, and control forces were matched as much as possible. The switches on the SAC head were used to support turning event markers on and off.

The sidearm controller (SAC) and collective were installed and positioned according to specifications provided by Sikorsky and were identical in arrangement to the 2002 Comanche VMS simulation.



Figure 11. Comanche 4-Axis Controller.



Figure 12. Collective Control Head.

1.8.2 Helmet-Mounted Display

The simulation utilized a ProView 50 HMD manufactured by Kaiser Electro-Optics on loan from the Comanche Portable Cockpit (fig. 13). The ProView 50 is a biocular display with a VGA (600 x 480 @ 60 Hz) active-matrix, liquid-crystal display. The field-of-view was 28° vertical by 49° horizontal with 25° overlap.

This display had a lower resolution and reduced FOV than the Comanche HIDSS system. The HIDSS display was to have active matrix LCDs, with SXGA resolution (1280 x 1024) and the field of view is 35° vertical by 52° horizontal with a minimum 17° overlap.

The same ProView 50 HMD was used to support Comanche Sim I. It is important to note that 1) minimal negative feedback was received by evaluation pilots on this matter during the 2002 Comanche simulation, and 2) the diminished FOV and resolution was constant across all experiment manipulations and therefore did not bias comparisons. The contrast of the FLIR sensor scene as viewed through the HMD produced a Level 2 usable cue environment (UCE 2), and resulted in a larger dependence on the symbology than the outside scene to complete the maneuvers. This was considered a desirable affect. Standards for the maneuver were based on a UCE 2 visual scene.

The symbology images for the HMD were generated by an SGI PC computer. The symbology overlaid the outside scene images produced by the image generator when combined in the HMD.

Comanche HIDSS



Kaiser ProView 50



Figure 13. Helmet-Mounted Display.

1.8.3 Head Tracker

The simulation utilized a Polhemus "Fasttrack" magnetic head tracker (fig. 14). The magnetic sensor was mounted to the cab above and to the rear of the pilot's head. The transmitter was mounted to the top of the HMD. A thorough mapping of the head-tracker envelope was accomplished during the simulation set-up. A method for boresighting the head tracker was installed to ensure each pilot's head position was in the head-tracker box prior to each pilot's first flight of the simulation session.



Figure 14. Polhemus Head Tracker.

1.8.4 Image Generator for the HMD

An Evans and Sutherland Image Generator, (CGI) Model 3000 (ESIG 3000), generated the FLIR image visual display for the HMD. The database used for the simulation was an in-house database of the Monterey Bay area. A terrain map of the database is shown in figure 15. The simulation evaluations were conducted using the FLIR mode only.

1.8.5 Panel-Mounted Display

The simulation used a single panel-mounted display. The display was an 8" x 8" flat panel. It was set up as a moving map depicting terrain relief, flight route, and aircraft present position with track-up. This display was only used for the tactical maneuvers (contour and NOE) and provided the pilots with additional situational awareness cues.



Figure 15. Plan View of Terrain Database.

1.9 Simulation Cab Performance Validation and Checkout

1.9.1 Math Model Performance Validation

The Comanche math model was validated during Comanche Sim I in 2002. During that experiment it was checked out by the VMS engineering staff along with on-site assistance from a Boeing flight controls engineer using check cases supplied by Boeing. The model is an accurate, non-linear, large angle, free flight math model of the Comanche airframe, engine, drive-train, and flight controls. No changes were made to the model since the 2002 simulation experiment.

The model was implemented during the pre-simulation ground checkout phase of this experiment in the F-Cab cockpit. The controllers were set up according to the Sikorsky design specifications. Plots of the controller characteristics were made for documentation. The AFDD project pilot checked out the combination of math model and controllers by flying a myriad of tasks from a pre-test matrix that validated performance against the PVIM specifications. The operation of the head tracker, visual system, and HMD were also verified during these trials.

The F-Cab was then moved to the motion-base beam and the same checkout was flown while the cab was in motion. Motion tuning trials of the flight maneuvers were flown to adjust motion cues as necessary to ensure they were appropriate for the maneuvers flown during the test.

Once all local validation checks were completed, an Army test pilot from the Comanche Combined Test Team (who had flown the actual aircraft) performed verification flights in the VMS. He flew specific maneuvers and measured the results against the design specification for the actual aircraft. He also provided subjective comments concerning the handling qualities of the simulator in a written after-action report. Deficiencies were recorded and analyzed by the simulation team. All deficiencies that would affect the results of the experiment were fixed.

A visiting Sikorsky human factors engineer (also a test pilot) verified the symbology drivers and visual performance. The process included a look at the design, movement, and functionality of each symbol, comparing performance to the most current version of the PVIMS design specification. Only minor deficiencies were noted and were corrected immediately.

SECTION 2. SIMULATION EXECUTION

2.1 Training and Test Procedure

The simulation was performed over a period of four weeks. Groups of one or two pilots were scheduled each day throughout the test period. Each pilot spent four to five days completing training and the test requirements.

Test pilots were given documentation on all maneuvers and performance parameters in advance of testing. Both classroom instruction and simulation cab familiarization occurred prior to practice of the evaluation maneuvers. Each pilot flew a series of specific maneuvers using each of the symbology sets (Contact Analog, compressed, or hybrid). The maneuvers are detailed in the Evaluation Flight Task section below. Practice runs were flown prior to data runs for each maneuver. Each maneuver, except the tactical maneuver, was flown in both directions, left and right. Each pilot completed a criterion task to a desired performance standard before data collection was initiated.

After executing an evaluation maneuver, pilots completed a Weighting of Rating Scales (Appendix D). NASA-TLX subscales were presented in pair-wise comparisons for the purpose of weighting the scale that was perceived to more significantly contribute to workload for a particular task. Upon completion of data trials for a maneuver, pilots rated workload on each of the subscales. Weighted overall workload scores were calculated for each pilot by applying the scale weights to the raw subscale ratings for a maneuver.

Once testing within a symbology set concluded, pilots' subjective ratings on the effectiveness of the display symbology were collected in an online questionnaire. Specific symbols (i.e., horizon line reference) were rated separately for usefulness and ease or difficulty to control relative to aircraft axes. Additional pilot comments were collected in post-experiment debriefings.

The simulation project pilot conducted all pilot training. The training sessions involved both ground school and simulator flight training. During ground school the pilots were presented an overview of the functionality of each symbol in each of the symbol sets. Separate sessions were taught for Contact Analog and MIL-STD-1295 just prior to data collection for that symbology. Training also included an explanation of the flight controls and flight control modes, and an overview of the flight test maneuvers and standards. Subject pilots were given instruction during structured familiarization flights in the VMS. Interaction of the flight control inputs and the symbology response was experienced. Training flights in a specific symbology set preceded the data runs requiring the use of that particular symbol set. Once the pilots were comfortable with the controls, displays, and symbology, they were required to fly an evaluation task to a specified performance standard before being allowed to proceed to the flight-test phase. A training syllabus is presented in Appendix A.

2.1.1 Evaluation Maneuvers

The maneuvers flown during this experiment and shown below were intended to be realistic tasks that would be performed by Army pilots consistent with the Comanche Scout/Attack mission. These tasks and performance standards were validated during the checkout phase of the simulation by project test pilots. An Army experimental test pilot from the Comanche Combined Test Team further independently validated the test maneuvers.

The simulation utilized two levels of flight tasks to evaluate the effectiveness of the Comanche symbology. The levels included both a constrained handling qualities maneuver as well as a less constrained emergency procedure and tactical terrain flight profiles. The handling qualities maneuver was a hover turn bob-up, which is a modified ADS-33 task. The unusual attitude recovery was a discrete task developed from the Attack Helicopter Aircrew Training Manual that was intended to measure the usability of the heading tape, horizon line, altitude, and other symbology in maintaining situational awareness during an emergency situation. The mission-related tasks simulated a tactical reconnaissance mission and required use of all of the primary flight symbology in contour and NOE flight modes.

A detailed description of the tasks, conditions, and performance standards follows:

2.1.2 Hovering Turn (Criterion Maneuver)

This task was not used as a data collection task. Its purpose was to determine whether the test subject pilots had the required skill in handling the aircraft and using the symbology to execute a constrained task to acceptable standards. The hover turn (fig. 16) is an ADS-33 task and the criteria for adequate performance were the published UCE 2 performance criteria.

- a. Reference: ADS-33, March 2000, par 3.11.17, TC 1-251, ATM Task 1107, Hovering Flight, ADS-46 (Draft), June 1998, Par. 7.9.1.
- b. Objectives: This maneuver checks the pilot's ability to use the display symbology to recover from a rapid hovering turn with sufficient precision to fire a weapon. This is an aircraft pointing exercise.
- c. Requirements: This maneuver was flown using a precise target heading approximately 180° from the initial aircraft heading.
- d. Maneuver: From a stabilized hover at an altitude of not less than 20 ft, complete a rapid 180° hovering turn to line up with a specified heading while maintaining starting position over the ground and altitude. Turns will be completed in both directions.

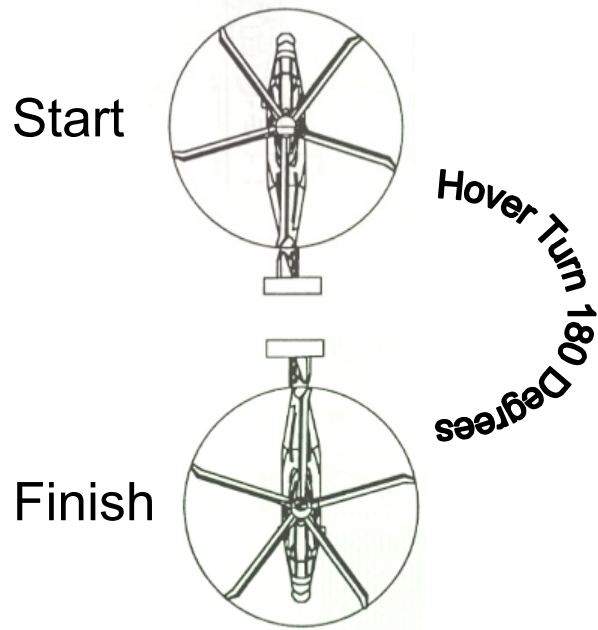


Figure 16. Hovering Turn.

e. Performance criteria:

Desired performance:

- Maintain longitudinal and lateral position within 6 ft of start position.
- Maintain altitude within ± 3 ft.
- Stabilize final aircraft heading within $\pm 5^\circ$.
- Complete the turn within 15 seconds from the initiation of the maneuver.

Adequate performance:

- Maintain longitudinal and lateral position within 12 ft of start position.
- Maintain altitude within ± 6 ft.
- Stabilize final aircraft heading within $\pm 10^\circ$.
- Complete the turn within 15 seconds from the initiation.

2.1.3 Hover Turn Bob-up

The pilot's head must be turned approximately 45° in the direction of turn prior to initiating the maneuver. The pilot will initiate a 90° hover turn while simultaneously executing a bob-up maneuver to 50-ft AGL above the initialization altitude of 10 ft (60-ft AGL) (see fig. 17).

- a. Reference: ADS-46 (Draft), June 1998, Par. 7.9.1, and 7.9.3, ADS-33, March 2000, Par. 3.11.6, 4.2.2, TC 1-251, ATM Task 1107, Hovering Flight, and Task 1151, Masking and Unmasking.
- b. Objectives: This maneuver checks the pilot's ability to use the display symbology to control a rapid hovering turn coupled with a rapid bob-up maneuver with sufficient precision to fire a weapon after completion of the climbing turn. This simulates rising vertically from a masked firing position while quickly turning to engage a target 90° off axis.
- c. Requirements: This maneuver will begin on a cardinal heading at approximately 10-ft. AGL. The pilot will turn 90° while simultaneously climbing to 60-ft AGL.
- d. Maneuver: This maneuver represents the combining of two different maneuvers specified in the references above. Those maneuvers are the turn to target and the hover bob-up. From a stabilized hover at an altitude of approximately 10 ft, the pilot will turn his head approximately 45° in the direction of the turn. The pilot will complete a 90° hovering turn while simultaneously climbing to a hover altitude of 60-ft AGL. The objective will be to arrive at 60-ft AGL at approximately the same time the specified heading alignment is achieved. Turns will be completed in both directions. The pilot's head may be repositioned as desired after commencing the maneuver.

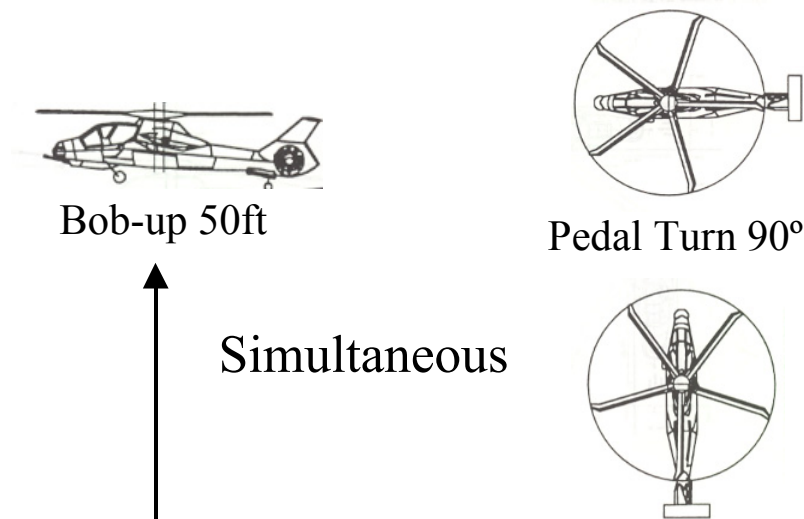


Figure 17. Hover Turn Bob-up.

e. Performance criteria:

Desired performance:

- Maintain longitudinal and lateral position from the starting point within 6 ft.
- Climb to and maintain 60-ft AGL ± 5 ft.
- Stabilize final aircraft heading $\pm 4^\circ$ of the target.
- VSI less than 100 fpm up/down
- Complete the turn in 15 seconds or less from the initiation.

Adequate performance:

- Maintain longitudinal and lateral position of a selected point on the aircraft within 10 ft of a selected point on the ground.
- Climb to and maintain 60-ft AGL ± 10 ft.
- Stabilize final aircraft heading $\pm 6^\circ$ of the target.
- VSI less than 200 fpm up/down
- Complete the turn in 20 seconds or less from the initiation.

2.1.4 Unusual Attitude Recovery

Symbology sets designated as primary flight symbology must be capable of assisting the pilot in recovering from an unusual attitude caused by inadvertent flight into instrument meteorological conditions or spatial disorientation caused by other factors (fig. 18). This is considered an emergency maneuver. As such, the simulator evaluation included extreme attitudes, both angle of bank coupled with extreme pitch angles.

- a. Reference: ADS-46 (Draft), June 1998, Par. 7.12.1. TC 1-251, Aircrew Training Manual, AH-64 Attack Helicopter, Task 1245.
- b. Objectives: There are three objectives for this test: 1) The first is to check the adequacy of the attitude symbology, 2) Check the utility of the display in allowing the pilot to recognize and recover from unusual attitudes, and 3) Check for undesired pilot-vehicle-display dynamics during extreme conditions.
- c. Requirements: Four different combinations of pitch and bank entries will be flown.
- d. Maneuver: The aircraft will be initialized in a decelerating attitude at 20 kts and 70-ft AGL. The simulator operator will fly the aircraft into a predetermined unusual attitude at which point the flight controls will be given to the evaluation pilot to recover the aircraft. The pilot must recover to a straight and level attitude with minimal vertical rates using standard UA recovery procedures.



Figure 18. Low Altitude Unusual Attitude Recovery.

e. Performance criteria:

Desired performance:

- Appropriate initial control input
- Stabilize wings level $\pm 5^\circ$ angle of bank
- Stabilize a constant heading
- Less than 100 fpm vertical rate
- Recovery time 15 seconds or less from initiation

Adequate performance:

- Appropriate initial control input
- Stabilize wings level $\pm 10^\circ$ angle of bank
- Stabilize a constant heading
- Less than 200 fpm vertical rate
- Recovery time 20 seconds or less from initiation

2.1.5 Tactical Mission

Execution of this task requires the use of nearly every primary flight symbol presented on the HMD while flying a realistic flight profile representative of one of Comanche's primary missions.

- a. Reference: TC 1-251, Aircrew Training Manual, Attack Helicopter, AH-64D, April 1998, Task 1035, Terrain Flight.

- b. Objectives: While using the HMD as the primary flight reference, perform contour and NOE flight profiles to designated waypoints while maintaining altitudes and airspeeds appropriate to the flight mode. The pilot will be searching for ground targets during the NOE portion of this mission.
- c. Requirements: AFCS will be used during the maneuver. The maneuvers were flown on pre-designated courses in the terrain database.

2.1.6 Contour Flight Mode

Contour flight is characterized by constant altitude above ground level (AGL) (generally between 50–150 feet) and relatively constant airspeed (typically between 60–80 knots) depending on vegetation, obstacles, and visual conditions (fig. 19). The flight profile generally follows the contour of the surface of the earth.

The contour flight was initialized over a road. The pilot was required to follow the road that curves through rolling terrain using contour flight techniques until arriving at the destination waypoint. During the flight, the experimenters commanded two altitude and two airspeed changes. The pilot was required to comply as rapidly as possible and to report stable at the new parameter. Time and accuracy in achieving and maintaining the new parameter were measured.

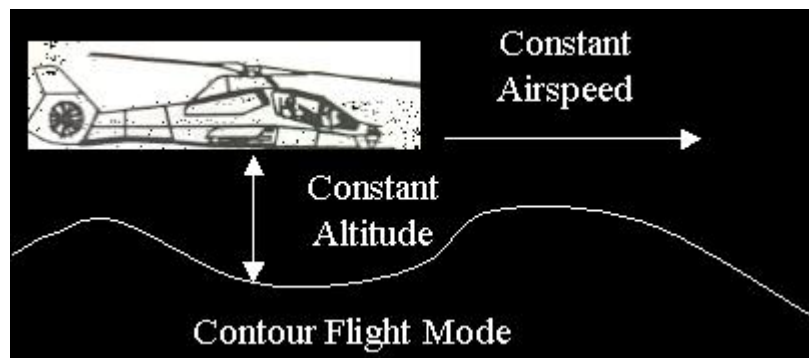


Figure 19. Contour Flight Mode.

Desired performance contour flight:

- Maintain a flight profile that generally conforms to the contour of the earth.
- Maintain assigned airspeed ± 5 kts.
- Maintain assigned altitude ± 10 ft.
- Maintain aircraft in trim.

Adequate performance contour flight:

- Maintain a flight profile that generally conforms to the contours of the earth.
- Maintain assigned airspeed ± 10 kts.

- Maintain assigned altitude ± 15 ft.
- Maintain aircraft in trim.

2.1.7 NOE Flight Mode

NOE flight is characterized as flight at varying altitudes and airspeeds (variable < 45 kts) as close to the earth's surface as vegetation, obstacles, and visual conditions permit (fig. 20). NOE flight was conducted through rolling terrain along a generally prescribed route along four consecutive waypoints. While navigating the NOE flightpath, the pilot used visual scanning techniques to identify targets (vehicles) to the left and right of the aircraft. The pilot was required to call out the azimuth from present position of each vehicle sighted. The time from target sighting to calling out the azimuth was recorded along with the difference between the perceived and actual target azimuth.

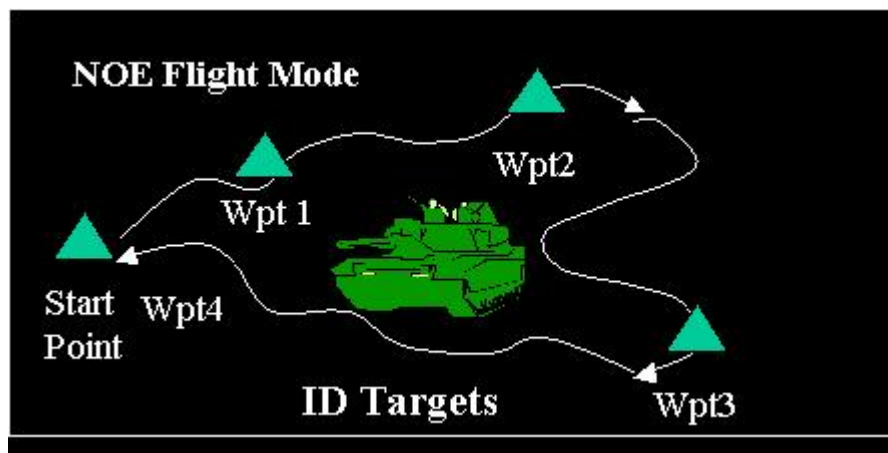


Figure 20. NOE Flight Mode.

d. Performance criteria:

Desired performance NOE flight:

- Maintain an altitude that allows safe obstacle clearance while remaining as close to the earth as possible while flying a Nap-of-the-Earth profile.
- Maintain airspeed appropriate for the terrain and visual conditions (generally < 60 kts).
- Use flight symbology to accurately navigate to all waypoints.
- Accurately call out azimuth to target.

Adequate performance NOE flight:

- Maintain an altitude that allows safe obstacle clearance while remaining as close to the earth as possible while flying a nap-of-the-earth profile.
- Maintain airspeed appropriate for the terrain and visual conditions (generally < 60 kts).

- Use flight symbology to accurately navigate to all waypoints.
- Accurately call out azimuth to target.

2.2 Performance Evaluation Tools

2.2.1 Data Collection

Several different data collection methods were used to support the simulation as detailed in the paragraphs below.

Show Print and RUNDUM Data Set

RUNDUM data (e.g., time, position, altitude, heading, other) were collected at 60 Hz, recording the variables specified for each maneuver.

The data collected on the SHOW PRINT file were used as post-run feedback of the pilot's performance following each maneuver. The data were in summary format and included the selected performance parameters tailored for each task.

The parameters for the SHOW PRINT and RUNDUM data are in Appendix B.

X-Y Plotter

An X-Y plotter (electronic form) provided researchers with a real-time graphical representation of aircraft vertical and horizontal position during the maneuvers.

2.2.2 Handling Qualities Ratings (HQRs)

Cooper/Harper HQRs were taken following the completion of each hover bob-up maneuver data set. Pilot comments were also recorded that provided rationale for the rating. A copy of the Cooper/Harper HQR rating scale can be found in Appendix C. Pilot comments can be examined in Appendix G.

2.2.3 NASA-TLX

NASA-TLX workload rating scale data were collected immediately following each maneuver data set. The scale was filled out based on a subjective assessment made by the pilot concerning mental, physical, and temporal demand. This test instrument also captured data concerning how the pilot felt about his performance of the task, the level of effort put into the task, and the level of frustration experienced in completing the maneuver. A copy of a sample NASA-TLX data collection sheet is in Appendix D.

SECTION 3. SIMULATION TEST RESULTS

3.1 Simulation Test Results Overview

Objective and subjective simulation test results are presented in this section. Objective analysis includes actual data collected with respect to the performance parameters set up for each maneuver (e.g., time to complete, heading, altitude, and position) at the time the maneuver was completed. Pilot performance data concerning each performance parameter were statistically analyzed, and a comparison was made between Contact Analog and MIL-STD-1295 compressed symbology. The statistical analysis information presented shows averaged performance. More detailed performance analyses are presented in Appendix F.

The subjective analysis section examines the summarized results of the HQRs, NASA-TLX workload ratings, situational awareness ratings, and the results of the on-line survey. Pilot comments are also summarized in this section with unabridged comments located in Appendix G. In some cases, the subjective results pointed out more significant differences in performance than were indicated by the objective results.

3.2 Objective Test Results

Six pilots completed four evaluative maneuvers. The maneuvers were hover bob-up, unusual attitude, contour flight, and NOE flight with target azimuth ID. A 2 x 2 x 4 within-subjects design ANOVA (Symbology x Block x Trial) with repeated measures was conducted separately on time, attitude, and position data for unusual attitude recovery, hover turn bob-up (position hold), and hover turn bob-up maneuvers completed in Comanche Automated Flight Control System (AFCS) mode. Those events that produced a statistically significant outcome are presented in the figures below. A total objective data set can be found in Appendix F.

Figure 21 shows that a significant main effect of symbology was found in recorded time to complete the hover turn bob-up (Position Hold ON) maneuver, $F(1, 5) = 18.03, p < .01$, such that 1295 symbology ($M = 13.35$) yielded more rapid maneuvering than Contact Analog symbology ($M = 15.37$). No significant differences between symbologies were found in time, attitude, or position data in all other maneuvers.

The results from NOE flights are shown in figures 22 and 23. Figure 22 revealed improved accuracy in heading to target estimation when utilizing Contact Analog symbology, $F(1, 5) = 12.67, p < .05$. Likewise, figure 23 shows that shorter response times from target recognition to heading callout were recorded utilizing Contact Analog symbology, $F(1, 5) = 13.84, p < .05$. These results clearly show that the head-referenced heading tape associated with the Contact Analog design was faster and more accurate in completing this task.

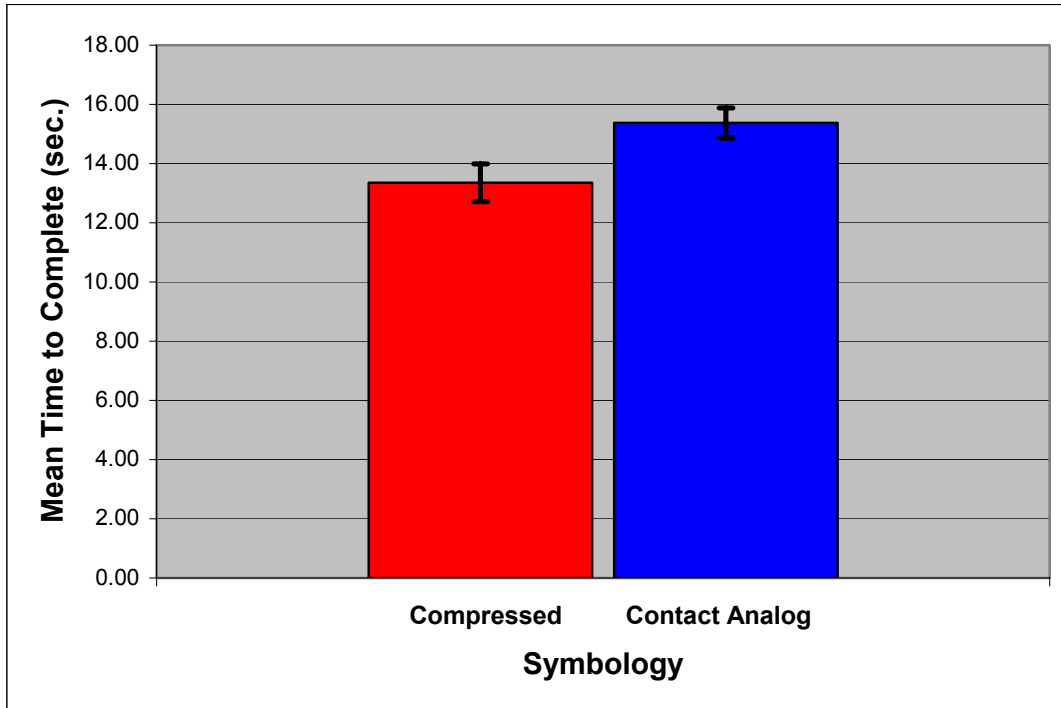


Figure 21. Hover Turn Bob-up Time to Complete (Position Hold).

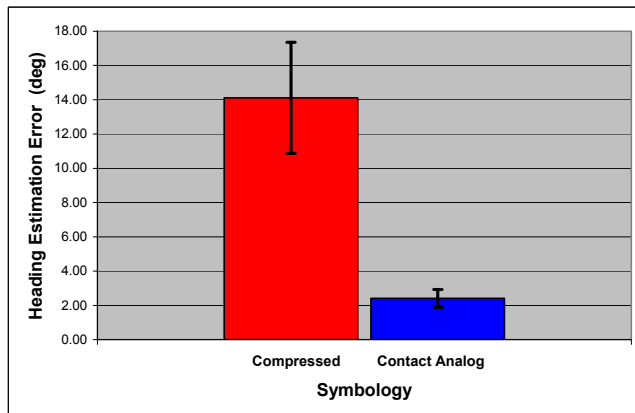


Figure 22. NOE Mission Performance: Accuracy of Heading to Target Estimation.

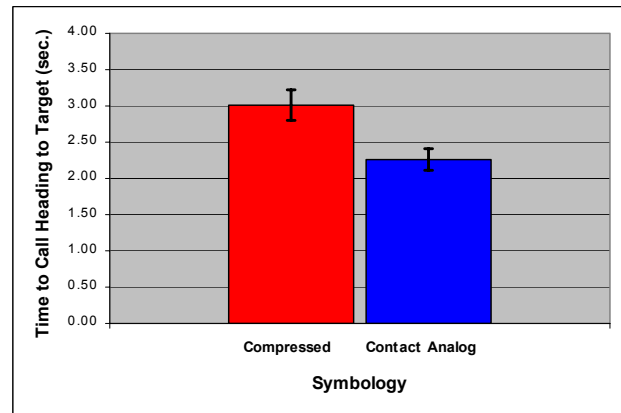


Figure 23. NOE Mission Performance: Mean time to Call Heading to Target.

TABLE 1. OBJECTIVE PERFORMANCE RESULTS SUMMARY

Maneuver	Compressed	Contact Analog
UA Recovery Time	Red	Red
Bob-up (AFCS) Longitudinal Error	Red	Red
Bob-up (AFCS) Lateral Error	Red	Red
UA Vertical Rate	Yellow	Yellow
Bob-up (VelStab) Lateral Error	Green	Yellow
Bob-up (VelStab) Time to Complete	Green	Yellow
Bob-up (AFCS) Time to Complete	Yellow	Yellow
NOE Heading to Target: Accuracy		7 X More Accurate
NOE Heading to Target: Speed		1.3 X Faster
	Green = Desired Yellow = Adequate Red = Exceeded adequate	

The summary of performance results presented in Table 1 shows that the average recovery time to complete the Unusual Attitude task exceeded adequate for both symbology sets. It also shows that pilots exceeded adequate standards with regard to holding lateral and longitudinal position with AFCS Hover Hold OFF using both symbology sets. Pilots flying both symbology sets only achieved adequate performance in maintaining the appropriate vertical rate measured during the UA maneuver. They also achieved adequate standards in the time to complete the bob-up with position hold OFF. These results clearly show that the decreased performance was experienced using both symbology sets with no significant performance difference between the two. The only maneuvers where performances differences were noted between symbology sets were the bob-up lateral error with VelStab ON, and in bob-up time to complete with VelStab ON. In both instances, performance with 1295 was desired whereas performance with Contact Analog was only adequate. The other notable difference between symbology sets was that the average pilot was 7 times more accurate and 1.3 times faster in calling out the heading to target using Contact Analog than when using the compressed heading tape on the 1295 symbology presentation. The importance and operational significance of this finding was previously discussed.

3.3 Subjective Test Results

Subjective test results are presented and analyzed below. Only those ratings that showed a significant finding are presented. Those subjective areas that were analyzed but did not show significant findings are presented in Appendix F. Handling qualities ratings (HQRs), NASA TLX workload ratings, and situational awareness ratings are presented in this section.

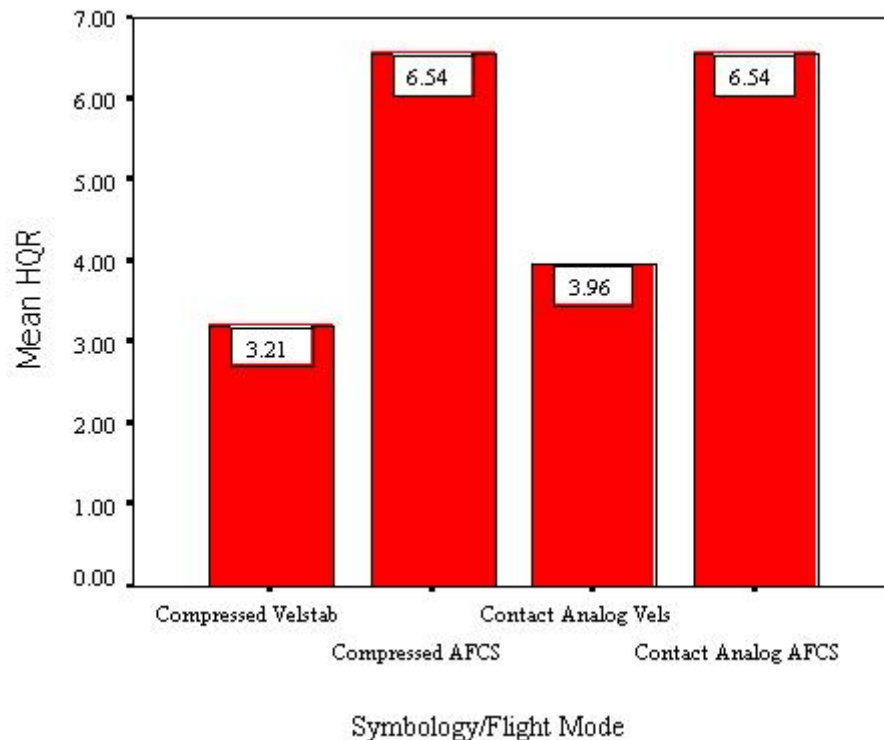


Figure 24. Bob-up HQRs VelStab Position Hold ON.

Figure 24 clearly shows a large difference in the difficulty of the maneuver when executing it with Position Hold ON (VelStab) versus Position Hold OFF (AFCS). MIL-STD-1295 symbology shows an average rating of HQR 3. This translates to “Fair handling qualities with some mildly unpleasant deficiencies requiring minimal pilot compensation required for desired performance.” Contact Analog symbology was rated approximately HQR 4. This translates to “Minor deficiencies requiring considerable pilot compensation to achieve desired performance.” Pilots were able to achieve desired standards flying both symbology sets. The difference here was that it required slightly greater pilot compensation to fly Contact Analog symbology.

Flying either symbology set using AFCS (Position Hold OFF) showed an almost doubling of the HQRs with higher scores meaning worse handling qualities. Pilots rated Contact Analog and compressed 1295 symbology identically with an average rating of 6.54. This means some scored HQR 7 and some HQR 6. An HQR of 6 translates to “Very objectionable but tolerable deficiencies requiring extensive pilot compensation to attain adequate performance.” An HQR 7 means “Major

deficiencies. Adequate performance not obtainable with maximum pilot compensation. Controllability not in question.” This clearly shows that without aircraft Position Hold, this was a very workload intensive task that required a great deal of pilot compensation to achieve adequate performance. This chart clearly shows, however, that there were no differences between symbology sets. It is possible that position keeping without position hold may have affected performance so severely that no performance differences were found between symbologies. Potential contributors to the difficulty of this task were the reduced usable cue environment looking at the outside scene and the scaling of the velocity vector and acceleration cue.

Figure 25 shows that on a scale of 0 to 100, the average overall workload for both compressed and Contact Analog symbology was slightly above the middle rating, which is not excessive. It also clearly indicates that there was very little difference in the workload between Contact Analog and MIL-STD-1295 compressed symbology. This finding was surprising because both verbal and written pilot comments led the research team to an expectation of higher workload associated with Contact Analog symbology. Figure 26 indicates that the highest workload experienced was for the bob-up maneuver followed by the unusual-attitude recovery. The workload was calculated for the AFCS flight control mode with Position Hold OFF. There were no significant differences between Contact Analog and compressed symbology for any of the individual maneuvers.

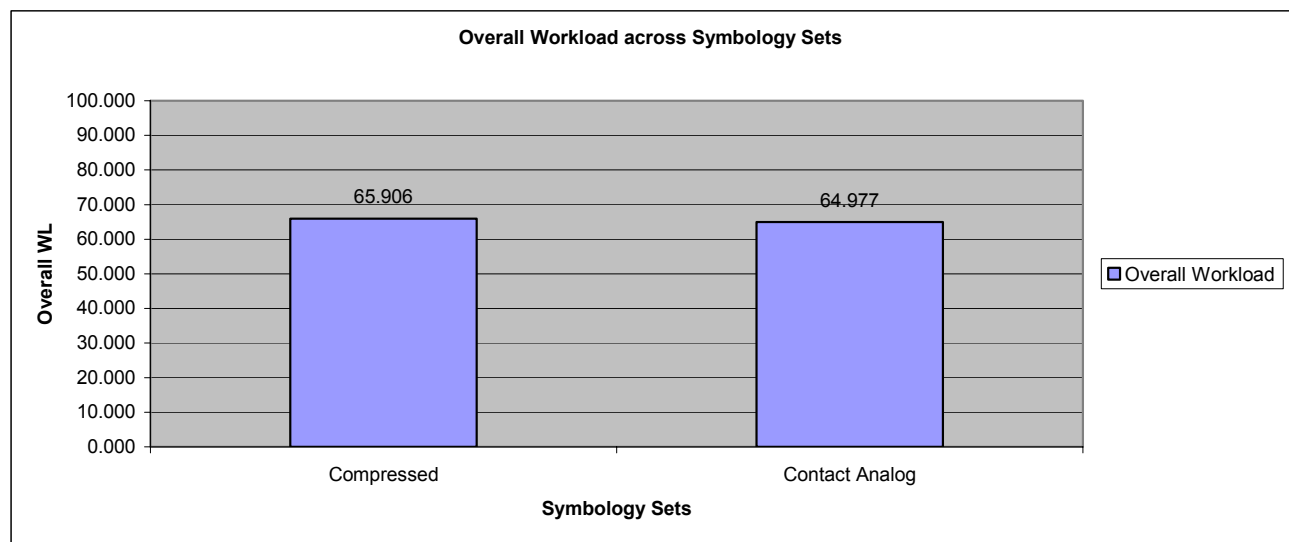


Figure 25. NASA-TLX Workload Ratings.

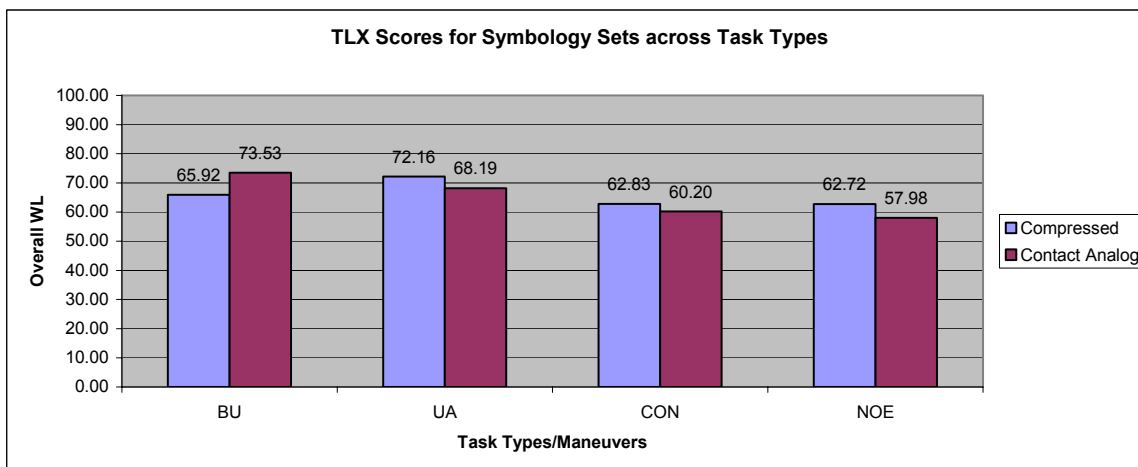


Figure 26. NASA-TLX Scores for All Maneuvers Completed.

Situational awareness (SA) was defined to the pilots as follows: *Knowledge of the interrelationships between other aircraft or objects and one's own position in time and in 3-dimensional space, such that one may operate in the best offensive and defensive manner possible.* Pilots were asked to rate their situational awareness (SA) for each maneuver flown on a scale from left to right beginning with very low to very high. Situational awareness ratings shown in figure 27 indicate there were no significant differences between symbology sets. The statistics shown above were the average ratings given by all pilots combined and averaged for all tasks flown. SA ratings were taken following the completion of each individual maneuver for each symbology and flight control mode. Once again, these statistical results seemed inconsistent with the written and verbal comments received from the pilots. There were frequent comments related to the lack of situational awareness recorded with the HQRs and also during the post-simulation reviews.

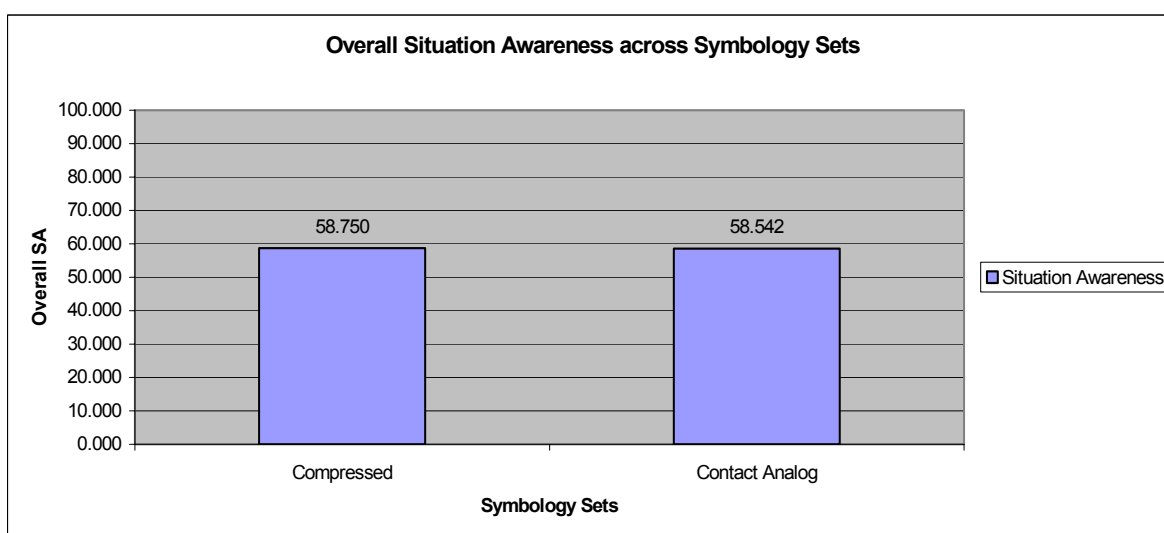


Figure 27. Averaged Situational Awareness Ratings for All Tasks.

Figure 28 shows the SA ratings for the individual tasks flown. This detailed analysis shows no significant differences between symbology sets when looking at the individual maneuvers. SA was better for the hover bob-up task and worse for the terrain flight tasks. This was a predictable result given the reduced visual cues provided by the FLIR image while executing near-earth flight maneuvers in rolling and wooded terrain.

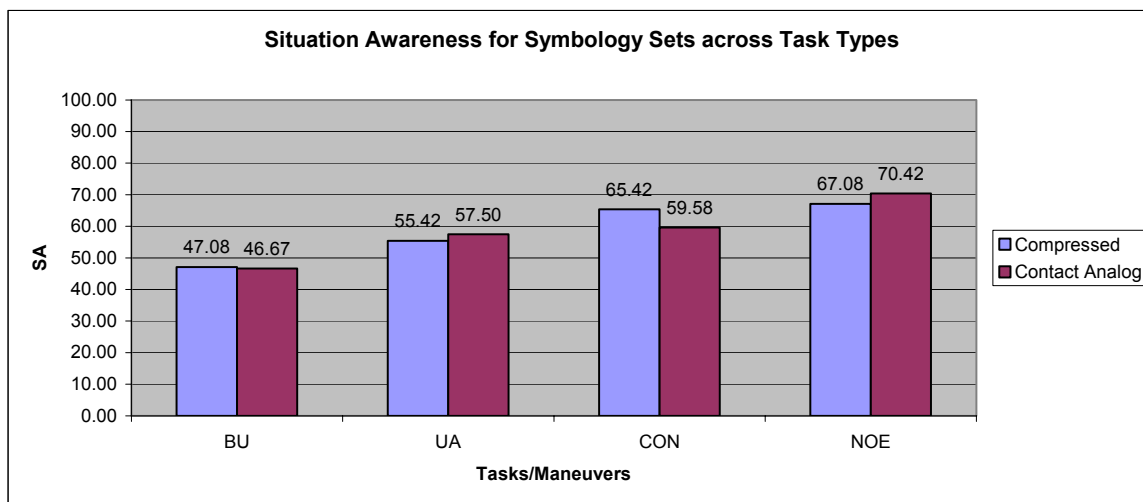


Figure 28. Situational Awareness Ratings for Individual Tasks.

A predicted result that was not yielded was the SA ratings for the unusual-attitude maneuver. The differences in the horizon line design philosophy between the symbology sets was expected to show a contrast during this maneuver. The Contact Analog design fixes the horizon line to the true horizon, whereas the MIL-STD-1295 horizon line is screen-fixed. The Contact Analog design caused the horizon line to disappear from view during nose-up attitudes, leaving no visual horizon reference except the blank sky. In spite of this fact, pilots were able to level the aircraft quickly enough to manage this deficiency. The 1295 screen-fixed horizon line and iron wings were in view at all times during the maneuver. Although all pilots commented on the lack of a Contact Analog horizon reference during the UA, they did not seem to reflect those comments in the SA ratings.

Figure 29 shows the averaged handling-qualities ratings for the bob-up maneuver flying three hybrid symbology sets using two different flight control modes. The only VelStab selectable mode engaged for this maneuver was Position Hold ON. The primary difference between the two test conditions was that the hover position over the ground was automatically held by VelStab for one condition, whereas the position was held by pilot input for the AFCS condition.

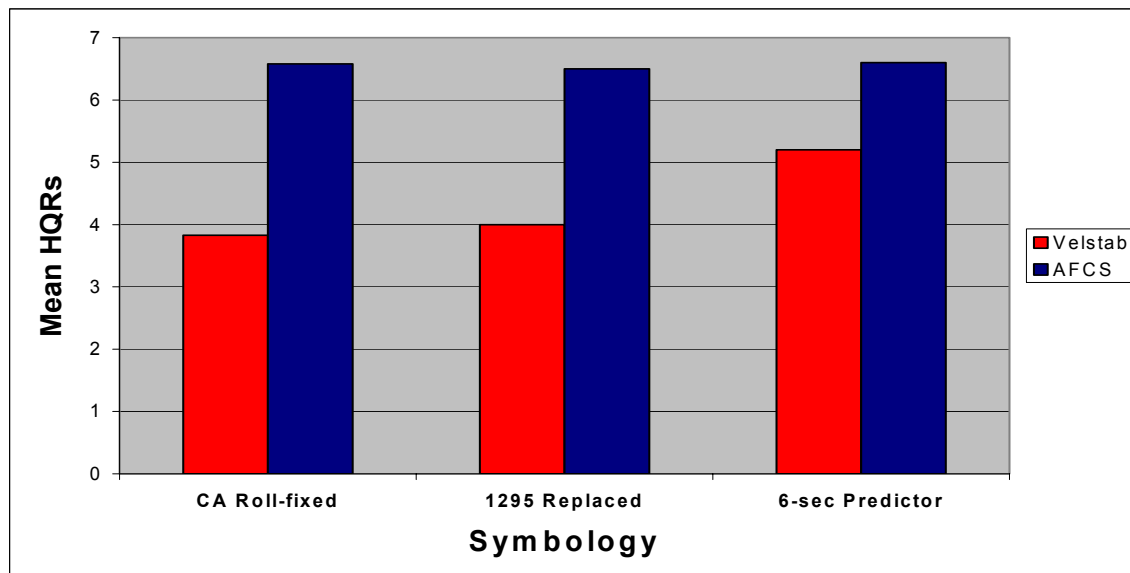


Figure 29. Hybrid Symbology HQRs – Bob-up.

The difference in workload between the two flight control modes was evident in the average HQRs reflected in the data. The data show a very high workload in the hand-flown AFCS mode. This likely confounded any distinguishable differences between the three hybrid symbology sets. In the VelStab Position Hold mode, an HQR of 4 shown for the CA roll-fixed and 1295 replaced hybrids is characterized by “Minor deficiencies. Desired performance required considerable pilot compensation.” HQR 5 represented by the 6-sec predictor translates to “Moderately objectionable deficiencies. Adequate performance requires considerable pilot compensation.” The major difference between HQR 4 and 5 is that HQR 5 is the breakpoint for moving from a desirable performance rating to an adequate rating. An average HQR of 6.5 was scored for all three hybrid symbology sets flown in the AFCS mode (between HQR 6 and HQR 7, there is no formal HQR 6.5). An HQR 6 is defined as “Very objectionable but tolerable deficiencies. Adequate performance requires extensive pilot compensation.” An HQR 7 means “Major deficiencies. Adequate performance not obtainable with maximum pilot compensation. Controllability not in question.” The 6.5 rating means pilots were only able to achieve adequate performance about half the time but the aircraft was never out of control.

The drift deviation from the starting hover position in the AFCS mode often exceeded 45 feet laterally or longitudinally and sometimes both. The amount of drift was not predictable and difficult to control given the scaling of the hover symbology. For this simulation there was no “home plate” symbol that pilots could use to maintain position. That symbol was subsequently implemented in the Sikorsky Engineering Development Simulator. It is unknown whether that symbol has been tested. The operational significance of the excessive amount of drift recorded in the AFCS is unknown.

To summarize, in a comparison of means calculated from NASA-TLX ratings, collapsed across subscales, no significant difference was found as an effect of symbology condition. Additionally, aircraft handling quality ratings (HQRs) did not differ as a result of symbology condition for the

hover turn bob-up maneuvers. Ratings on both NASA-TLX and HQRs revealed no differences in perceived workload, situational awareness, or aircraft handling qualities for compressed and Contact Analog symbologies.

3.4 Online Questionnaire Results

Pilots' subjective ratings on the effectiveness of the display symbology were collected in an online questionnaire following testing within a symbology set. Selected individual display symbols (i.e., horizon line reference) were rated individually to determine usefulness in completing the task and ease or difficulty in controlling related aircraft axes of motion.

The following items were rated utilizing the scale found in Appendix E. Ratings were taken in an online format with mouse input on a slider scale with endpoints corresponding to those listed. Significant findings of variance as a result of symbology have been graphed. Only those ratings that produced a significant finding are presented.

3.4.1 Legend for All Graphs

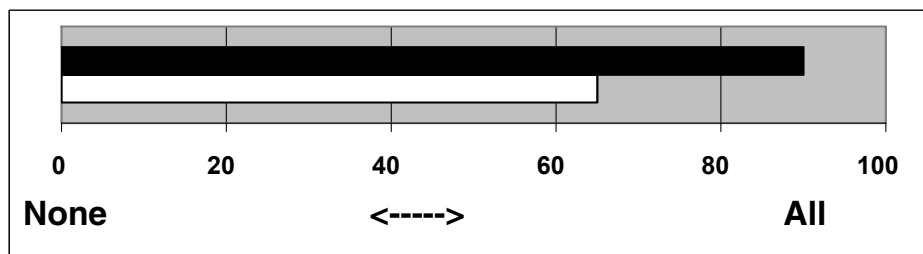
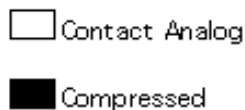


Figure 30. Average Rating of Correct Symbol Position within a Symbology Set.

Figure 30 shows that pilots rated the position of the symbols in the 1295 compressed symbology set to be nearly correct (90%) for all symbols. The rating for Contact Analog was only about 65%, meaning that nearly a third of the symbols were not considered to be correctly positioned. Pilots commented that the Contact Analog symbology set was too widespread. The position of the symbols was pushed toward the outer edges of the usable HMD display area. The design rationale was reportedly to declutter the central viewing area of the display to allow the pilot to better see targets or objects of interest without symbology interference. Pilots reported that positioning the symbols outward slowed their crosscheck and increased workload. The 1295 symbology was positioned much closer to the central viewing area of the display and therefore received a more favorable rating.

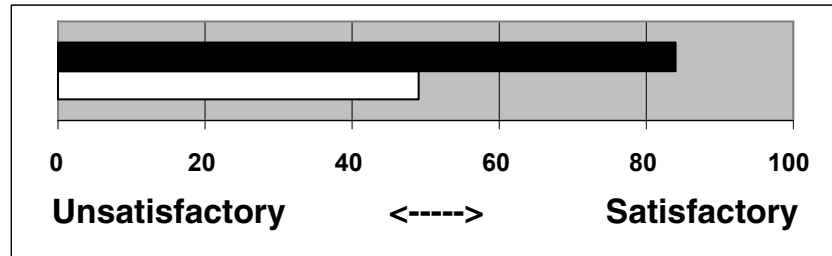


Figure 31. Horizon Reference Line Readability for Each Symbology Set.

Pilots' satisfaction with the readability of the 1295 horizon line was approximately 85% compared with only 48% for Contact Analog (fig. 31). The 1295 horizon line was screen-fixed. The relationship between the horizon line and the iron wings was constant regardless of the pilot's head position. The Contact Analog horizon line was fixed on the true horizon and allowed the gap in the center of the line to move with the pilot's head. The iron wings aircraft referenced them viewable only when looking straight forward over the nose of the aircraft (much like a virtual HUD). The earth-referenced horizon line design feature caused the horizon line to remain fixed on the true horizon during up and down head movement and aircraft pitch movement. The horizon line was therefore not visible or usable during portions of maneuvers such as an unusual attitude, steep descents, or other maneuvers where the aircraft or pilot's head was up or down. This directly affected the Contact Analog readability ratings.

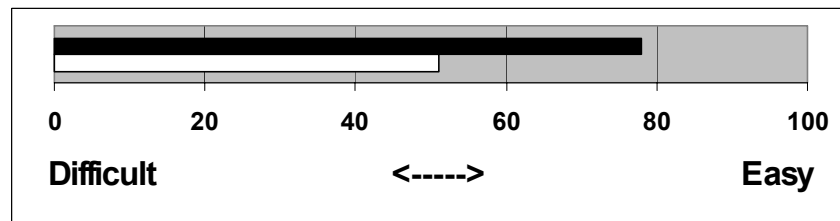


Figure 32. Ease with Which Pilots Could Control Aircraft Pitch.

Pilots rated control of aircraft pitch at approximately 78% for the 1295 symbology set compared with only approximately 50% for Contact Analog (fig. 32). Comments in the above paragraph with reference to the horizon line are likely reflected in this rating. As stated previously, the 1295 horizon line was screen-fixed and appeared as though painted on the pilot's visor, moving with head movement and never-changing position in the central field of view. The position of the iron wings and the horizon line could be seen no matter where the pilot was looking (i.e., up, down, left or right). With Contact Analog, the iron wings were aircraft-referenced, meaning they remained positioned over the nose of the aircraft and could only be viewed by the pilot when looking relatively straight forward. When looking off-axis during turns (a maneuver requirement) the iron wings could not be seen and the pilot had no pitch reference symbol for use in controlling aircraft attitude. In addition, the gap in the Contact Analog was much wider than the width of the iron wings. Therefore, there was no way to precisely match the level of the wings with the horizon line. Pilots

could not superimpose the iron wings over the horizon line to achieve a precise level attitude, as is common practice with more traditional attitude reference symbology.

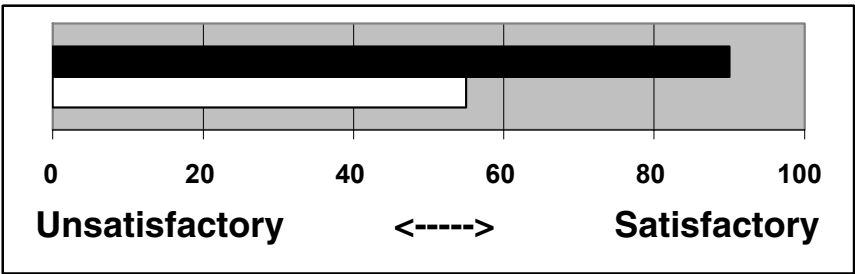


Figure 33. Vertical Situation Indicator Readability for Each Symbology Set.

Pilots preferred the VSI readability of the 1295 symbology (fig. 33) over Contact Analog at a rate of 90% satisfied compared with approximately 55% satisfied for Contact Analog. Based on pilot comments, the most probable reason was the lack of a scale in the Contact Analog VSI that would provide an analog cue for determining rates. The length of the VSI line was the intended analog cue for determining rate of climb information with a digital readout at the bottom of the scale. Pilots found the length of the line to be a less compelling rate cue than the pointer against a fixed scale used in the 1295 symbology design.

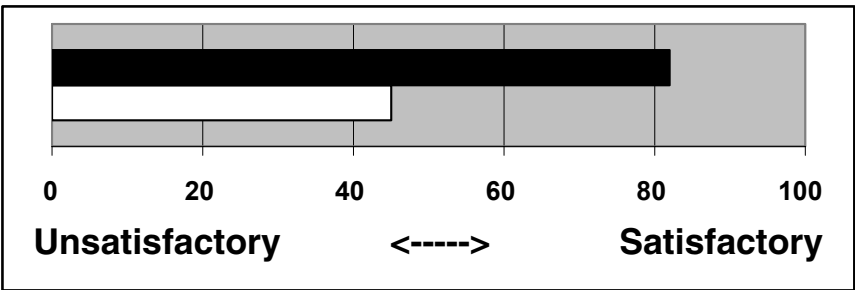


Figure 34. Dynamics of the Vertical Situation Indicator Symbol.

Satisfaction with the dynamics of the 1295 vertical rate symbology (fig. 34) was rated nearly twice that of Contact Analog. The primary reason given by pilots was that flying the pointer against a fixed vertical velocity scale provided a more predictable result when collective was increased or decreased during the hover bob-up or when holding an altitude during a rapid hovering turn. The Contact Analog VSI symbology had no scaling or index. It did present a digital readout. The beneficial effect of having a compelling analog rate indication was missing from the Contact Analog VSI symbology. This can also be seen in figure 35.

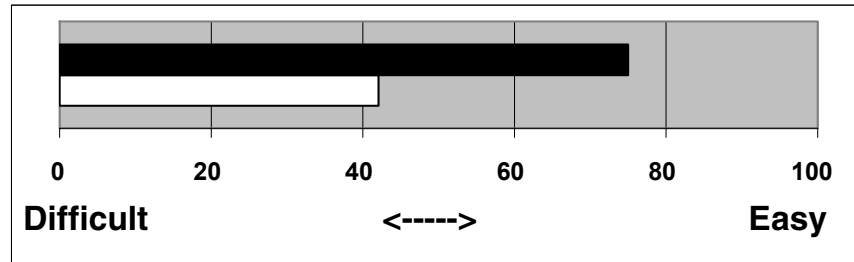


Figure 35. Control of Aircraft Rate of Climb and Descent.

Figures 33, 34, and 35 relate to the readability, dynamics, and ease of controlling vertical rates using both symbology sets. Ease of controlling vertical rates was rated much easier for 1295 symbology (75% easy) than for Contact Analog, which was weighted at approximately 42%. The 1295 design for the Vertical Speed Indicator (VSI) was a traditional moving pointer against a fixed scale that was graduated in 100 feet per minute (fpm) rate of climb or descent for the first 500 fpm and 500-fpm increments above that amount. The Contact Analog scale was a vertical line that grew longer with increased vertical rates and retracted to be invisible when rates were null. There was not a pointer or graduated scale associated with the line. However, there was a digital readout. Pilot comments reflected that maintaining a constant altitude or maintaining a constant rate of climb or descent was easier and required less workload using the pointer against the scale than using the Contact Analog line only with digital readout design. Pilots reported they could be more aggressive and precise in maintaining altitude in a level hover turn using the 1295 design. It was reportedly easier to null vertical rates using the pointer without getting into pilot-induced oscillation (PIO) associated with leveling out during the bob-up maneuver.

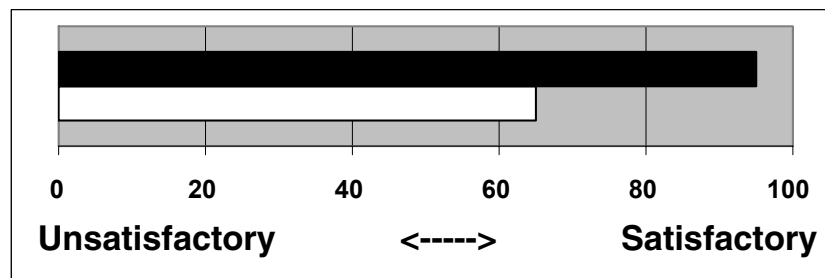


Figure 36. Satisfaction with the Dynamics of the Radar Altimeter Symbol.

Pilots reported a 95% satisfaction rate with the 1295 radar altimeter design compared to only a 63% satisfaction with the Contact Analog design (fig. 36). The 1295 radar altimeter design is a vertical thermometer against a fixed scale with various graduated heights in feet varying from 10-ft to 100-ft increments depending on altitude above the ground. It also provides a digital readout of altitude AGL in one-foot increments. The lower the altitude the more detailed the graduations. The Contact Analog design is a vertical thermometer type design with the first graduated scale at 100 feet, and two others at 500-ft increments separated by a non-linear distance between the graduations. There is

a digital readout at the base of the symbol graduated in one-foot increments. Pilots commented that the non-linear scaling of the Contact Analog design was misleading with regard to determining rates using the thermometer scale. They also commented on the need to have a scale in smaller increments for altitudes below 100-ft AGL for use in maintaining ground clearance during IGE hover maneuvers. With Contact Analog, pilots tended to use the digital readout alone as the primary source of rate and height information and the thermometer scale was not used.

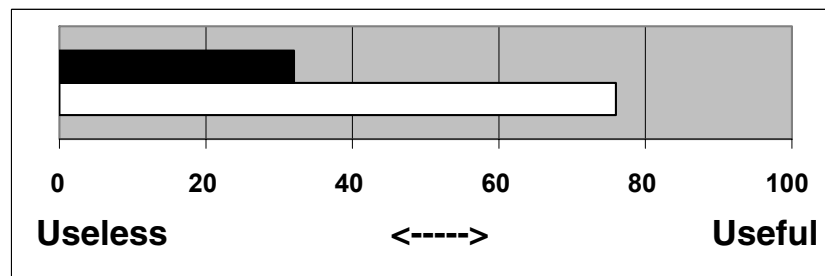


Figure 37. Use of Symbology for Accurately and Rapidly Reporting Heading to Target Information.

Pilots overwhelmingly preferred Contact Analog symbology over 1295 for rapidly reporting heading to target by a margin of almost two to one (fig. 37). A design feature of the head-tracked Contact Analog heading tape is that the heading tape can overlay a target through head movement and the target bearing can be quickly and accurately determined. Using the screen-fixed 1295 symbology, the pilot had to estimate how far the target was left or right of the aircraft centerline, and add or subtract that amount from the current aircraft heading. This took more time and was less accurate than using the head-tracked heading tape.

3.5 Summary of Subjective Questionnaire Ratings

Pilot ratings revealed major differences as a result of symbology type on 8 of 35 questions (fig. 38). Subjective ratings revealed the perceived benefit of 1295 compressed symbology for 7 of those 8 questions. Performance benefits included higher ratings of effectiveness for display items and greater ability to control related axes when utilizing 1295 compressed symbology. Specifically, pilots gave higher satisfaction ratings for readability of the horizon reference line ($M = 84\%$ satisfaction) and vertical speed indicator ($M = 90\%$ satisfaction). Furthermore, pilots viewed related dynamics of pitch ($M = 78\%$) and rate of climb/descent ($M = 75\%$) as more easily controlled when flying with 1295 symbology. Correct placement of symbols within 1295 symbology ($M = 90\%$ correct) was also rated higher than Contact Analog symbology ($M = 65\%$ correct). Lastly, pilots reported higher levels of satisfaction with the dynamics of the radar altimeter symbol in 1295 symbology ($M = 95\%$ satisfaction) than Contact Analog symbology ($M = 65\%$ satisfaction).

In a reversal of preference, pilots rated Contact Analog symbology more useful ($M = 76\%$) than 1295 symbology ($M = 28\%$) for accurately reporting heading to target information. This finding was not surprising considering the Contact Analog design philosophy that supports a veridical overlay of

heading information analogous to its world counterpart. It should be noted that pilots received feedback on the accuracy of their target heading reports prior to completing the online questionnaire.

In summary, pilots significantly favored 1295 symbology for the readability, placement, and dynamics of the symbols in flight maneuvers. Pilots judged Contact Analog symbology to be more useful than 1295 symbology for reporting target headings in an operational scenario.

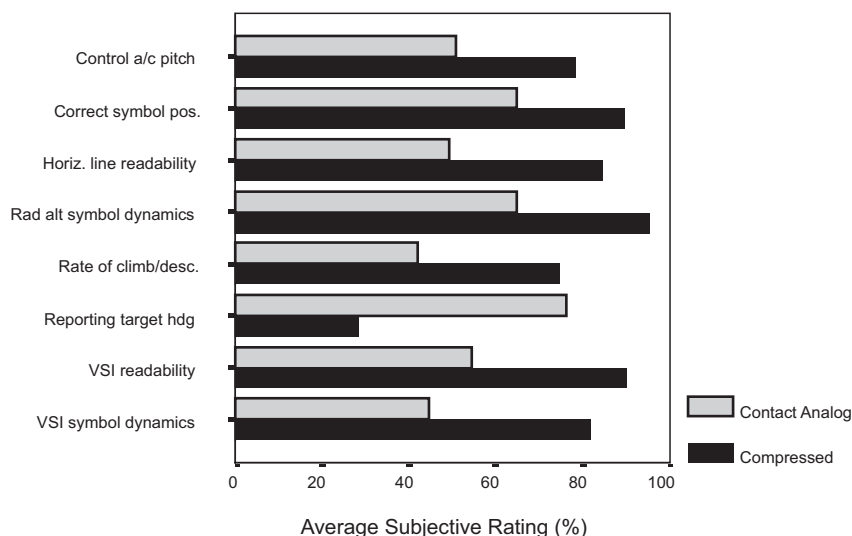


Figure 38. Summary of Online Questionnaire Ratings.

3.5.1 Summary of Pilot Comments

Pilot comments were recorded following the HQR ratings for the hover bob-up tasks after the completion of each maneuver for each symbology set. The total set of comments can be reviewed in Appendix G. Additional end-of-simulation summary comments were also recorded. Test team members reviewed all comments provided by the pilots in an attempt to find trends and common issues with respect to the symbology sets flown during the test. The following is a summary of the most repeated comments recorded by the test team.

3.5.2 Heading Tape

Six of six pilots stated that the Contact Analog heading tape moves too fast during rapid head movement or rapid aircraft yaw or turns to be usable as an analog cue. The heading tape blurs and is unreadable during turns. Pilots commented they had to constantly turn their head back over the nose to see the heading index.

Six of six pilots commented they could not differentiate between head movement and aircraft movement during turns or rapid yaw maneuvers when looking off axis. Combining heading tape movement with head movement gives the feeling that aircraft yaw rates are greater than actual rates. The ability to see the target heading during the majority of the turn using a compressed heading tape (1295) reduced workload and increased crosscheck time available for other parameters.

Pilots questioned the operational value of head-referencing the heading tape. Pilots stated there are other ways to get this same information without head-referencing the entire heading tape. Apache, for example, provides for an alternate crewmember HMD LOS bearing and a copilot/gunner (CPG) HMD LOS symbol, both located along the bottom of the compressed heading tape, to indicate the exact azimuth to a target that the pilot or CPG is looking at.

3.5.3 Horizon Line

Six of six pilots commented that the Contact Analog horizon line disappears from view during aircraft nose up/down or head up/down conditions, leaving the pilot with no horizon reference. Not having a visible horizon could present an unsafe situation.

Five of six pilots commented that the earth-referenced horizon line was difficult to use with respect to unusual attitudes and was often not present in the field of view. This can result in significant disorientation especially during the initial phases of an unusual-attitude recovery.

There were additional comments concerning the width of the gap in the middle of the horizon line. Recommendations were to reduce the width of the gap from 18° to something less where the tips of the iron wings would touch the horizon line in a level attitude. The design rationale for the 18° gap was reportedly to reduce clutter in the central viewing area of the HMD display. The comments on this subject indicated it was a lower priority issue and not flight critical.

3.5.4 Six-Second Predictor

Six of six pilots commented that the six-second predictor was not usable in stopping climb/descent at a desired radar altitude.

Six of six pilots commented that attempts to use the six-second predictor resulted in pilot-induced oscillations and longer times to stabilize at a desired altitude.

3.5.5 Symbology Position

All six pilots commented that the Contact Analog symbology was generally positioned too far to the outside edges of the display. They commented that the widespread symbology design increased workload, slowed crosscheck, and decreased readability. This reportedly resulted in longer maneuver completion times.

3.5.6 Torque Symbol

All six pilots commented that the torque symbol is positioned closer to the central viewing area of the display than more important symbology, such as the radar and barometric altitude symbology. Pilots commented that altitude information is more critical for situational awareness and survival than torque. Pilots used the digital portion of the torque symbology but felt the thermometer scale was of no use in executing the test maneuvers.

3.5.7 Hover Position Cue

All six pilots commented on the need for hover position symbology to determine the control inputs required for maintaining hover position. A hover position box was not provided in the Contact Analog symbology set used for this simulation. This symbol was specified in the PVIMS but at the time of the Ames simulation, it had not been implemented or tested by Sikorsky.

3.6 Validation of Test Results

The Technical Division Chief for PM Comanche directed that a single, coordinated position be established between the participating pilots and the test team members concerning the findings and recommendations of the HMD symbology test. This meant agreeing upon the meaning of the objective and subjective test findings and establishing a coordinated position concerning recommendations for improvements and the priority for addressing the recommendations. The coordinated results were briefed to the Comanche PM, and subsequently to the Sikorsky Chief Engineer for Comanche along with the Comanche Crew Station Working Group (CSWG) made up of both Government and Sikorsky technical personnel.

The test team carefully reviewed the objective and subjective test results to identify specific trends in preparation for briefing the participating pilots. This review looked for repeated pilot difficulties with certain tasks, repeated HQR comments, common subjective questionnaire ratings, and end-of-simulation interview comments. The team identified areas where a clear consensus was achieved by all or most of the six pilots concerning the symbology flown during the simulation. This review identified six Contact Analog symbols that warranted change. These were the heading tape, horizon line, overall symbology positioning in the FOV, the six-second radar altimeter predictor, the torque symbol, and the lack of hover position cue.

A prioritization rating scheme was developed that required the pilots to rate the seriousness of the perceived deficiencies in each of the six symbols. The prioritization scheme follows:

- (1) Must change now. Safety of flight, workload, or performance issue that must be addressed prior to flight.
- (2) Should be changed at the earliest opportunity. Violates best design practices, human factors principles. Should be changed in next block upgrade.
- (3) Nice to have. If possible, change at earliest convenience when making other modifications.

The test results were then briefed to the participating ATTC pilots and Ames pilots. Using the above rating scheme, the pilots arrived at a consensus opinion that of the six symbols identified as being problematic, three were considered to be a priority one for improvement. The priority one symbols were the heading tape, horizon line, and six-second predictor. Safety of flight concerns was the primary reason given for the priority-one recommendation. The ATTC pilots were unanimous in their recommendations, whereas the Ames pilots were mixed between priority two and three. The detailed results (figs. 39, 40, and 41) were as follows:

3.6.1 Heading Tape

Comments: Moves too fast to be used as an analog heading cue.

Tape movement cannot be differentiated between head and aircraft movement.

Priority Ratings: 1, 1, 1, 1, 2, 2

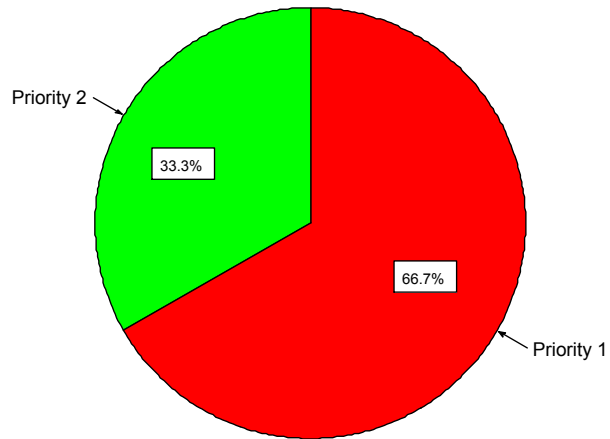


Figure 39. Heading Tape Modification Priority Ratings ($n = 6$).

3.6.2 Horizon Line

Comments: Disappears from field of view in nose up/down or head up/down conditions.

Priority Ratings: 1, 1, 1, 1, 2, 3

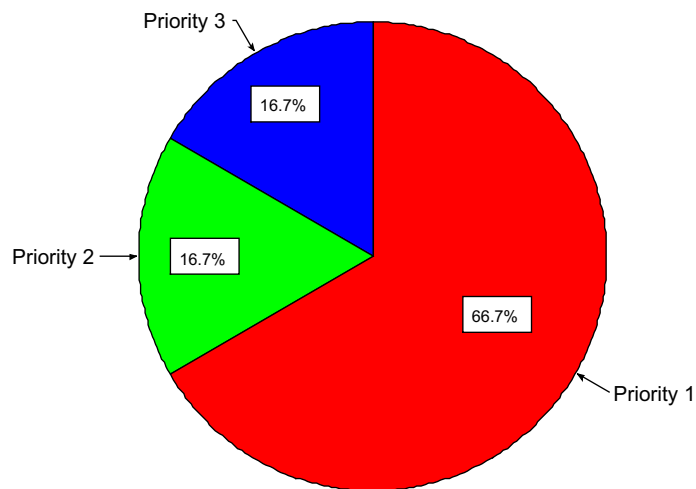


Figure 40. Horizon Line Modification Priority Ratings ($n = 6$).

3.6.3 Six-Second Predictor

Comments: Existing predictor design is not usable for precisely stopping a vertical rate at a desired altitude. Predictor causes pilot-induced oscillations (PIO).

Priority to Remove: 1, 1, 1, 1, 1, 1

Priority to Modify: 2, 2, 2, 2, 2, 3

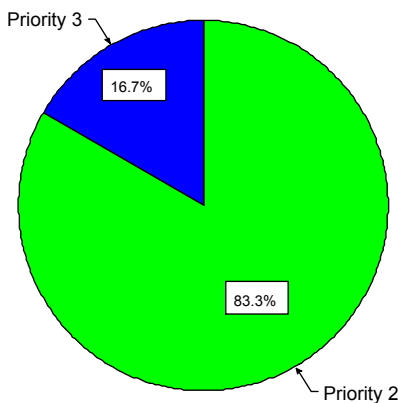


Figure 41. Six-second Predictor Modification* Priority Ratings ($n = 6$).

**Note: Unanimous consensus on removal of six-second predictor if no further design modifications*

These findings were included in a comprehensive briefing that was presented to both the Comanche PMO, the Sikorsky Chief Engineer for Comanche, and to the CSWG on October 22–23, 2003.

3.7 AFDD Test Team Summary and Conclusions

The test team came to the following conclusions after taking all objective and subjective data into account. These were briefed to the Comanche PMO and to the CSWG during the October 2003 briefings referenced in the above paragraph.

The simulation results show no objective test data that would warrant restricting experimental test pilots from flying constrained tasks.

ATTC safety-of-flight issues warrant further testing and modification of the design of selected symbols in the Contact Analog symbology set. The symbols which were rated priority 1, safety-of-flight were:

- Heading Tape
- Horizon Line
- Six-Second Predictor

Small but consistent advantages were recorded for the MIL-STD-1295 symbology design when executing ADS-33 constrained tasks in both this simulation as well as the previous Comanche simulation.

The azimuth-to-target task favored the Contact Analog heading tape design. No other performance differences were recorded for the operational maneuvers (NOE, contour flight modes).

There were consistent and strong pilot comments supporting the MIL-STD-1295 design over Contact Analog in both this current simulation and in Comanche Sim I.

Sikorsky's Crew Station Design Group has put together a plan for modifying and testing a redesigned Contact Analog symbology set. This plan was briefed at the CSWG meeting in January 2004.

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APPENDIX A. SYMBOLOGY AND TEST MANEUVER TRAINING

Each evaluation pilot will be provided training to familiarize the pilot with the simulation cab, flight controls, and HMD symbology. The training sessions for symbology familiarization will follow the schedule below. Progress through the training sessions will be monitored to determine when the pilot is ready to make data evaluations. The training is estimated to take 8–10 hours as follows:

1-hour classroom	Contact Analog Symbology
1-hour classroom	Compressed Symbology
.5-hour classroom	Hybrid Symbology
1–2 hours simulator	Contact Analog Symbology - Fam + Training Tasks*
1–2 hours simulator	Compressed Symbology - Fam + Training Tasks*
1–2 hours simulator	Hybrid Symbology - Fam + Training Tasks*
.5-hour simulator	Contact Analog Symbology - Training Evaluation †
.5-hour simulator	Compressed Symbology - Training Evaluation †
.5-hour simulator	Hybrid Symbology - Training Evaluation †

Notes:

The order of training will be counterbalanced.

This training will be somewhat self-paced and some pilots may not require the full number of hours although they will be available.

* The familiarization flight will consist of structured instruction and free flight. This will be followed by practice on specific maneuvers similar to those that will be used in the experiment.

† The evaluation flight will consist of re-familiarization, and then a criterion task maneuver (hover turn) will be flown to the performance parameters defined by ADS-33. The pilot will have 3 attempts at the maneuver. Successful completion of the maneuver to standards will qualify the pilot to proceed to data evaluation. If a pilot cannot proceed, the project pilot will provide appropriate additional training prior to re-test.

APPENDIX B. DATA REQUIREMENTS FOR COMANCHE SIMULATION II

Experimenter & Pilot Control Requirements Post-Run Data File Requirements Post-Run Printout Requirements Raw Data File Requirements

For purposes of data recording and processing, there are six maneuvers listed in table 2:

TABLE 2. MANEUVERS

- | |
|---|
| A.) Hovering Turn
B.) Vertical Maneuver (note that this maneuver is deleted)
C.) Hover Turn Bob-up
D.) Unusual Attitude Recovery
E.) Contour Flight
F.) Nap-of-the-Earth (NOE) |
|---|

In the test plan, the contour flight and NOE are listed together as "tactical mission." A different raw and processed data file will be generated for each of the six maneuvers.

Most of the maneuvers have two or more possible starting positions, starting aircraft state, and/or desired direction of turn as listed in table 3:

TABLE 3. MANEUVERS WITH INITIAL CONDITIONS

- | |
|---|
| A1.) Hovering Turn, Left
A2.) Hovering Turn, Right (same initial conditions as A1)

B1.) Vertical Maneuver (note that this maneuver has been deleted)

C1.) Hover Turn Bob-up, Left
C2.) Hover Turn Bob-up, Right (same initial conditions as C1)

D1.) Unusual Attitude Recovery, Up, Right
D2.) Unusual Attitude Recovery, Up, Left
D3.) Unusual Attitude Recovery, Down, Right
D4.) Unusual Attitude Recovery, Down, Left

E1.) Contour Flight, Course #1, Forward
E2.) Contour Flight, Course #1, Reverse |
|---|

TABLE 3. CONTINUED

E3.) Contour Flight, Course #2, Forward E4.) Contour Flight, Course #2, Reverse E5.) Contour Flight, Course #3, Forward E6.) Contour Flight, Course #3, Reverse ----- F1.) NOE Flight, Course #1, Forward F2.) NOE Flight, Course #1, Reverse F3.) NOE Flight, Course #2, Forward F4.) NOE Flight, Course #2, Reverse F5.) NOE Flight, Course #3, Forward F6.) NOE Flight, Course #3, Reverse

Each type of maneuver (such as the four unusual-attitude recovery maneuvers D1, D2, D3, and D4) will generate the same raw data file, post-run (processed) data file, and printout. However, the initial conditions of the data run may be different.

The file-naming convention is listed in table 4:

TABLE 4. FILE NAMING CONVENTION

Raw data files shall have a .rnd extention. Processed data files shall have a .dat or .xls extention.

The experimenter has five toggle buttons and a momentary event marker as listed in table 5. The toggle buttons should light up to distinguish one state from the other. Status on a monitor is acceptable if lighting the button is difficult.

TABLE 5. EXPERIMENTER BUTTONS

1.) Toggle: Data Recording ON/OFF 2.) Toggle: Command Altitude High START/COMPLETE 3.) Toggle: Command Altitude Low START/COMPLETE 4.) Toggle: Command Airspeed START/COMPLETE 5.) Toggle: Command Airspeed Low START/COMPLETE 6.) Momentary: Target Provided Event Marker

The pilot has one momentary switch event marker as listed in table 6. In addition the pilot has an IC button to stop the simulation and go back to (paused) initial conditions.

TABLE 6. PILOT BUTTONS

- | |
|--|
| 1.) Momentary: Target Seen Event Marker
2.) IC button |
|--|

Each raw and processed data file consists of ASCII characters, (comma?) separated columns, (line-feed?) separated rows. The raw data files will have all information necessary for post-run reconstruction of the maneuver, including the 3D position, 3D linear velocities, and 3D orientation of the aircraft during the run. In addition, the raw data files must have the head orientation recorded (head position not required). The first row of the raw data file contains the text headers labeling each column of data. All data in the raw data file will be sampled at the same rate. Each row is a new sample.

Each post-run data file will have at least two rows. The first row consists of text headers labeling. The second row and subsequent rows have all the statistical data detailed later in this document.

Dependent Measures for Comanche Sim II Post-Run Data File and Printout

Note: Raw data file requirements are not yet listed in this document.

1. Hovering Turn (Criterion Task Only)

Post-run data file and printout (showprint):

Data recording starts when the experimenter's Data Recording button goes into the ON state. When the button transitions to the OFF state, the raw data file is saved, the post-run data file is generated and saved, and the post-run statistics printout is generated. The post-run data file and printout contain the following:

- 1) Run number
- 2) Date/time
- 3) Pilot number (ID)
- 4) Task and turn direction (i.e., Hovering Turn Left)
- 5) Longitudinal RMS* [min., max., RMS, performance label (desired, adequate, not adequate)]
- 6) Lateral RMS* [min., max., RMS, performance label (desired, adequate, not adequate)]
- 7) Altitude RMS [min., max., RMS, performance label (desired, adequate, not adequate)]
- 8) Final Heading Delta [performance label (desired, adequate, not adequate)]
- 9) Time to Complete [performance label (desired, adequate, not adequate)]—the length of time the Data Recording button is in the ON state.

*Calculated from pilot's seat position (or FLIR sensor?), not CG

The hovering turn printout is shown in table 7.

TABLE 7. HOVERING TURN PRINTOUT

<i>Pilot ID</i>		<i>Task/turn direction</i>	<i>Run number</i>	<i>Date</i>	<i>Time</i>
Statistics	Value	Min.	Max.	RMS	Performance Label
Longitudinal		X	X	X	X
Lateral		X	X	X	X
Altitude		X	X	X	X
Final Heading	X				X
Time to complete	X				X

2. Hover Turn Bob-up

Data recording starts when the experimenter's Data Recording button goes into the ON state. When the button transitions to the OFF state, the raw data file is saved, the post-run data file is generated and saved, and the post-run statistics printout is generated. The post-run data file and printout contain the following:

Post-run data file and printout (showprint):

- 1) Run number
- 2) Date/time
- 3) Pilot number (ID)
- 4) Task and turn direction (i.e., hover turn bob-up left)
- 5) Longitudinal RMS [min., max., RMS, performance label (desired, adequate, not adequate)]
- 6) Lateral RMS [min., max., RMS, performance label (desired, adequate, not adequate)]
- 7) Max. Altitude
- 8) Final Altitude
- 9) Final Heading
- 10) Time to Complete [performance label (desired, adequate, not adequate)]—the time the Data Recording button is in the ON state

The hover bob-up printout is shown in table 8.

TABLE 8. HOVER BOB-UP PRINTOUT

Pilot ID		Task/turn direction	Run number	Date	Time
Statistics	Value	Min.	Max.	RMS	Performance Label
Longitudinal		X	X	X	X
Lateral		X	X	X	X
Altitude			X		
Final Altitude	X				X
Final Heading	X				X
Time to complete	X				X

3. Unusual Attitude Recovery

Data recording starts when the experimenter's Data Recording button goes into the ON state. When the button transitions to the OFF state, the raw data file is saved, the post-run data file is generated and saved, and the post-run statistics printout is generated. The post-run data file and printout contain the following:

Post-run data file and printout (showprint):

- 1) Run number
- 2) Date/time
- 3) Pilot number (ID)
- 4) Task and Initial Position (i.e., Unusual Attitude Down Left)
- 5) Roll Angle
- 6) Pitch Angle
- 7) Pitch Rate?
- 8) Roll Rate?
- 9) Yaw Rate?
- 10) VSI vertical rate
- 11) Recovery time [performance label (desired, adequate, not adequate)] - the time the Data Recording switch is in the ON state
- 12) Number of ground strikes

Append the data in table 9 to the processed data file and printout for the state of the aircraft at the beginning of the run, and at the end of the run.

TABLE 9. UNUSUAL ATTITUDE RECOVERY PRINTOUT

<i>Pilot ID</i>		<i>Task/Initial Position</i>	<i>Run number</i>	<i>Date</i>	<i>Time</i>
Statistics	Value				Performance Label
No. of ground strikes	X				
Final Roll Angle	X				X
Pitch Angle	X				X
Pitch Rate?	X				
Roll Rate?	X				
Yaw Rate?	X				
VSI vertical rate	X				X
Recovery time	X				X

4. Contour Flight (One of two elements of the Tactical Mission)

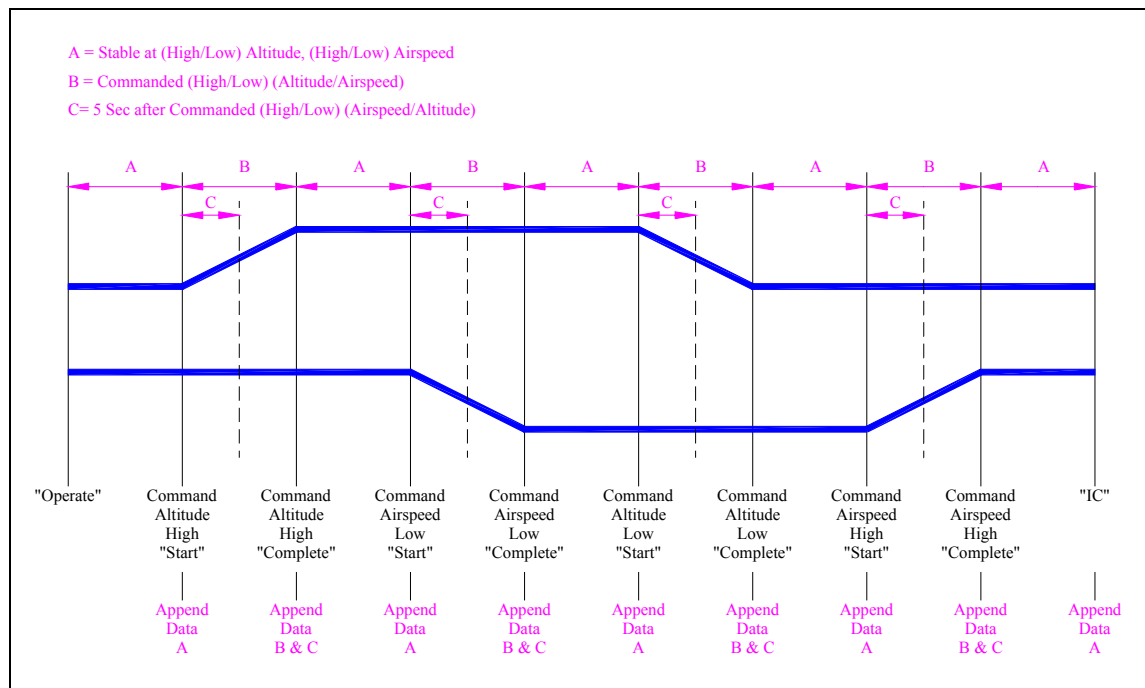


Figure 42. Data Recording Timing for Contour.

Post-run data file and printout (showprint):

Altitude high/low event marker

Airspeed high/low event marker

Altitude RMS

Airspeed RMS

Final Altitude Delta for Altitude event

Final Airspeed Delta for Airspeed event

Time to complete each "event" (experimenter button press marks end of event – delta between initial to final button press)

Pilot stick positions

There are five experimenter buttons used for this maneuver:

- 1.) Data Recording ON/OFF
- 2.) Command Altitude High START/COMPLETE
- 3.) Command Altitude Low START/COMPLETE
- 4.) Command Airspeed High START/COMPLETE
- 5.) Command Airspeed Low START/COMPLETE

The raw data file is recording data continuously from Data Recording ON to Data Recording OFF.

Each time a command button is pressed (either state), or the Data Recording button goes to the OFF state, data are appended to the post-run data file and printout.

Only one of the four command buttons may be ON at a time. Ignore any additional ON presses until the four command buttons are all OFF. When data are appended to the post-run file or printout, the data shall be as shown in table 10:

TABLE 10. CONTOUR FLIGHT PRINTOUT

<i>Pilot ID</i>	<i>Course</i>	<i>Latency</i>	<i>Run number</i>	<i>Date</i>	<i>Time</i>
Statistics	Value	Min.	Max.	RMSE***	Performance Label
State of command *	X				
Altitude		X	X	X	
Airspeed		X	X	X	
Cyclic Long.		X	X		
Cyclic Lat.		X	X		
Collective		X	X		
Time to complete **	X				

*State of the command is the text labeled A, B, or C. Please insert the correct text (High or Low, Altitude or Airspeed).

**Where Time to Complete is the time from a Command Button START (1 of 4) to the same button COMPLETE (Time B). Time to Complete is not recorded or printed for any of the "Stable" conditions listed previously (Time A).

***RMSE is referenced to the desired radar altitude or airspeed. The VMS software must keep track of what the current desired altitude and airspeed is, based on the last buttons pressed for altitude and airspeed (or initial conditions).

5. NOE Flight (One of Two Elements of the Tactical Mission)

Post-run data file and printout (showprint):

Altitude
Airspeed
Target number
Heading to current target
Time between a target pop-up and the pilot's event marker
Time between the pilot's event marker and the experimenter's event marker
Number of ground strikes
Number of tree strikes
Flight time above 50 ft.
Total time of run

There are three buttons used for this maneuver:

- | |
|---|
| 1.) Experimenter's Data Recording ON/OFF
2.) Experimenter's "Target Provided" Event Marker
3.) Pilot's "Target Seen" Event Marker |
|---|

The raw data file is recording data continuously from Data Recording ON to Data Recording OFF.

Every time the experimenter's event button is pressed, the following statistics (table 11) are appended to the post-run file and printout:

TABLE 11. NAP-OF-THE-EARTH DATA APPENDED TO PRINTOUT DURING RUN

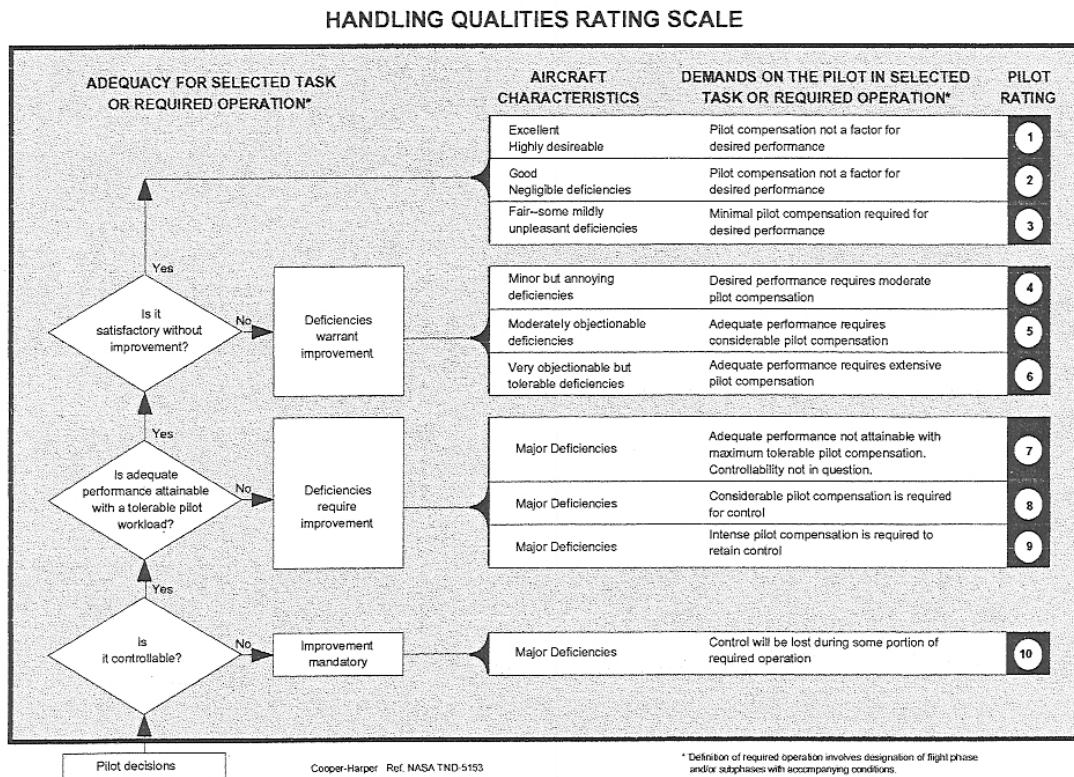
<i>Pilot ID</i>	<i>Course</i>	<i>Latency</i>	<i>Run number</i>	<i>Date</i>	<i>Time</i>
Statistics	Value				
Target No.	X				
Heading to current target at pilot event button press	X				
Aircraft heading at pilot event button	X				
Time between target pop-up and pilot event button	X Or "never"				
Time between pilot event button press and experimenter event button press	X Or "never"				

At the end of the run (when the experimenter changes the state of the Data Recording button to OFF) the following statistics (table 12) are appended to the post-run file and printout:

TABLE 12. NAP-OF-THE-EARTH DATA APPENDED TO PRINTOUT AT END OF RUN.

	Value	Min	Max	RMS	Mean
Altitude		X	X	X	X
Airspeed		X	X	X	X
No. of ground strikes	X				
No. of tree strikes	X				
Flight Time above 50 ft.	X				
Time to complete run	X				

APPENDIX C. COOPER/HARPER HANDLING QUALITIES RATING SCALES



Cooper/Harper HQR Rating Scale

HQR 1. Excellent – Highly desirable. Pilot compensation not a factor for desired performance.

HQR 2. Good – Negligible deficiencies. Pilot compensation not a factor for desired performance.

HQR 3. Fair – Some mildly unpleasant deficiencies. Minimal pilot compensation required for desired performance.

HQR 4. Minor deficiencies. Desired performance required considerable pilot compensation.

HQR 5. Moderately objectionable deficiencies. Adequate performance requires considerable pilot compensation.

HQR 6. Very objectionable but tolerable deficiencies. Adequate performance requires extensive pilot compensation.

HQR 7. Major deficiencies. Adequate performance not obtainable with maximum pilot compensation. Controllability not in question.

HQR 8. Major deficiencies. Considerable pilot compensation is required for control.

HQR 9. Major deficiencies. Intense pilot compensation is required to retain control.

HQR 10. Major deficiencies. Control will be lost during some portion of required operation.

APPENDIX D. NASA-TLX RATING SHEET

Subject Instructions: Weights

Throughout this experiment the rating scales are used to assess your experiences in the different test conditions. Scales of this sort are extremely useful, but their utility suffers from the tendency people have to interpret them in individual ways. For example, some people feel that mental or temporal demands are the essential aspects of workload regardless of the effort they expended or the performance they achieved. Others feel that if they performed well the workload must have been low, and vice versa. Yet others feel that effort or feelings of frustration are the most important factors in workload, and so on. The results of previous studies have found every conceivable pattern of values. In addition, the factors that create levels of workload differ depending on the task. For example, some tasks might be difficult because they must be completed very quickly. Others may seem easy or hard because of the intensity of mental or physical effort required. Yet others feel difficult because they cannot be performed well, no matter how much effort is expended.

The evaluation you are about to perform is a technique that has been developed by NASA to assess the relative importance of six factors in determining how much workload you experienced. The procedure is simple: you will be given a sheet of paper with all possible pairs (omitting duplications) of rating scale titles (e.g., Mental Demands vs. Effort), and asked to circle the item that was more important to *your* experience of workload in the tasks that you will be performing in the experiment. Circle only one of the two scale titles on each line—the scale title that represents the more important contributor to workload for the specific tasks you will be performing in this experiment. When you are done, one of the two words in each pair should be circled.

After you have finished the entire sheet of pairs we will be able to use the pattern of your choices to create a weighted combination of the ratings from each test trial into a summary score for that trial. Please consider your choices carefully and make them consistent with how you will be using the rating scales during the particular task you were asked to evaluate. Don't think that there is any one *correct* pattern; we are only interested in your opinions. If you have any questions, please find the tester and ask them now. Thank you very much for your participation.

Name / ID: _____

Maneuver completed: _____

HQR _____

WEIGHTING OF RATING SCALES

Circle only one of the two scale titles on each line—the scale title that represents the more important contributor to workload for the tasks you will perform in the test.

Performance	Physical Demand
Mental Demand	Temporal Demand
Temporal Demand	Effort
Physical Demand	Frustration
Mental Demand	Effort
Performance	Effort
Frustration	Mental Demand
Physical Demand	Effort
Mental Demand	Performance
Temporal Demand	Performance
Mental Demand	Physical Demand
Temporal Demand	Frustration
Physical Demand	Temporal Demand
Frustration	Performance
Effort	Frustration

Subject ID: JoeSample

Task ID: _____

WORKLOAD and SITUATION AWARENESS RATING SHEET

MENTAL DEMAND



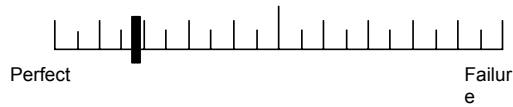
PHYSICAL DEMAND



TEMPORAL DEMAND



PERFORMANCE



EFFORT



FRUSTRATION



SITUATION AWARENESS: Knowledge of the interrelationships between others' [other aircraft or objects] and one's own position in time and in 3-dimensional space, such that one may operate in the best offensive and defensive manner possible.

Rate your level of situation awareness in the mission you just flew.



Sample NASA-TLX Workload Rating Form

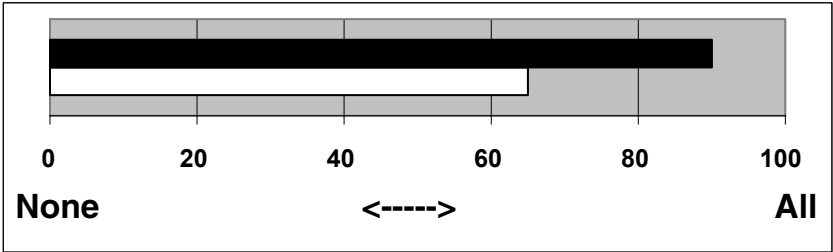
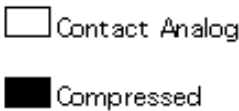
APPENDIX E. SUBJECTIVE QUESTIONNAIRE SCALES AND RESULTS

The following items were rated utilizing the scale found in the adjacent column. Ratings were taken in an online format with mouse input on a slider scale with endpoints corresponding to those listed. Significant findings of variance as a result of symbology have been graphed. Selected ratings that showed a significant result were repeated in the main body of this report and analyzed to determine cause.

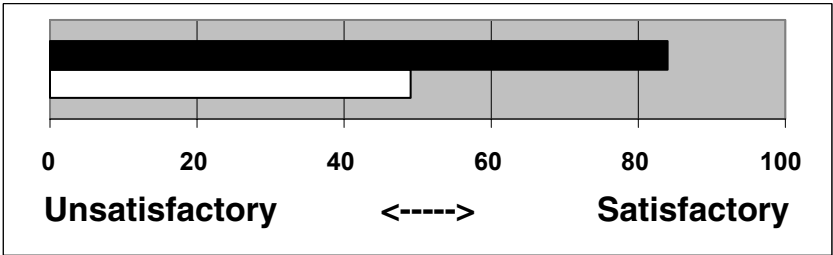
1. Symbology clutter	low-high
2. Correct symbol positioning	none-all
3. Tendency to shift attention	never-always
4. Ease of dividing/shifting attention	easy-difficult
5. Enhanced mission effectiveness	enhanced-degradation
6. Enhanced situation awareness	enhanced-degradation
11. Enhanced flight performance	enhanced-degradation
12. Enhanced mission performance	enhanced-degradation
13. Enhanced flight safety	enhanced-degradation
14. Aircraft roll control	easy-difficult
15. Aircraft yaw	easy-difficult
16. Aircraft pitch	easy-difficult
17. Aircraft rate of climb/descent	easy-difficult
18. Achieve and maintain hover	easy-difficult
19. Aircraft attitude control	easy-difficult
20. Aircraft heading control	easy-difficult
21. Aircraft airspeed control	easy-difficult
22. Waypoint navigation performance	easy-difficult
24. Accurately reporting heading to target in tactical scenarios	useless-useful
25. Rapidly reporting heading to target in tactical scenarios	useless-useful
26. Spatial orientation in the world	never-always
27. Altitude above the terrain	never-always
28. Aircraft's indicated airspeed	never-always
30a. Readability-horizon reference line	satisfactory-unsatisfactory
30b. Readability-heading tape	satisfactory-unsatisfactory
30c. Readability-radar altitude	satisfactory-unsatisfactory
30d. Readability-airspeed	satisfactory-unsatisfactory
30e. Readability-barometric altitude	satisfactory-unsatisfactory
30f. Readability-vertical situation indicator	satisfactory-unsatisfactory
31a. Symbol Dynamics-horizon reference line	satisfactory-unsatisfactory
31b. Symbol Dynamics-heading tape	satisfactory-unsatisfactory
31c. Symbol Dynamics-radar altitude	satisfactory-unsatisfactory
31d. Symbol Dynamics-airspeed	satisfactory-unsatisfactory
31e. Symbol Dynamics-barometric altitude	satisfactory-unsatisfactory
31f. Symbol Dynamics-vertical situation indicator	satisfactory-unsatisfactory

Legend for all graphs:

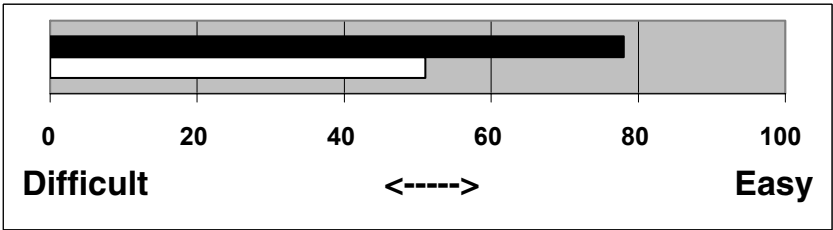
■	Compressed Symbology
□	Contact Analog Symbology



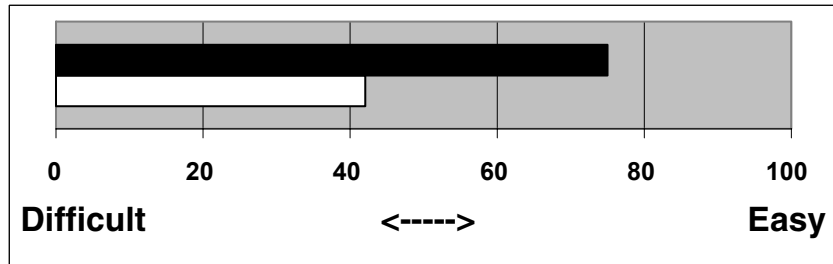
Average rating of correct symbol position within a symbology set ($n = 6$)



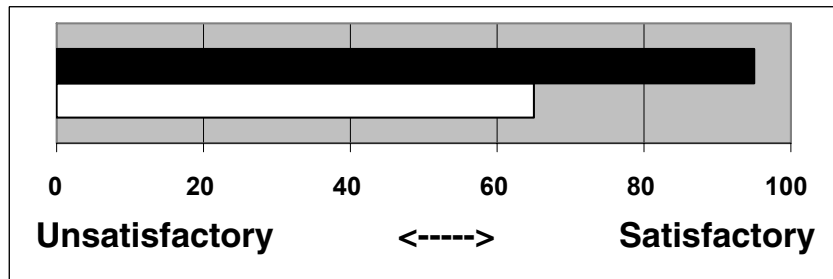
Rating of horizon reference line readability for each symbology set ($n = 6$)



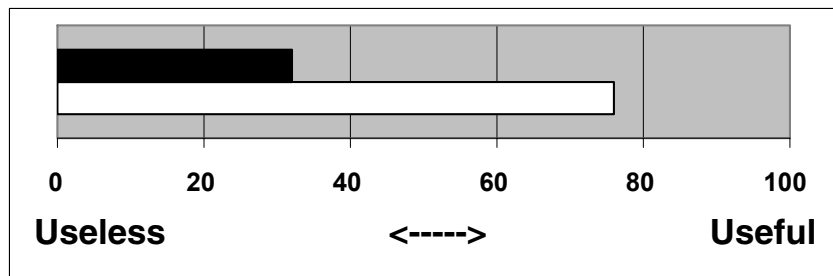
Rating of ease with which pilots could control aircraft pitch ($n = 6$)



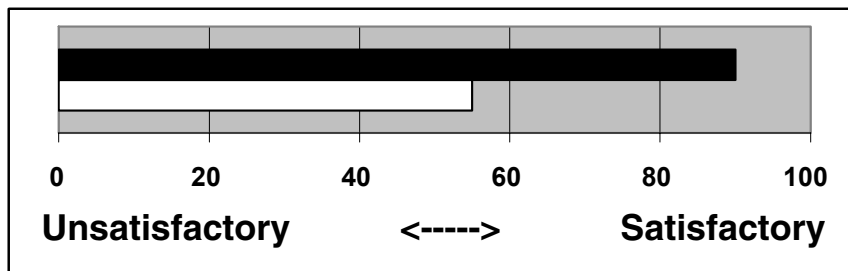
Rating of ease with which pilots could control aircraft rate of climb and descent ($n = 6$)



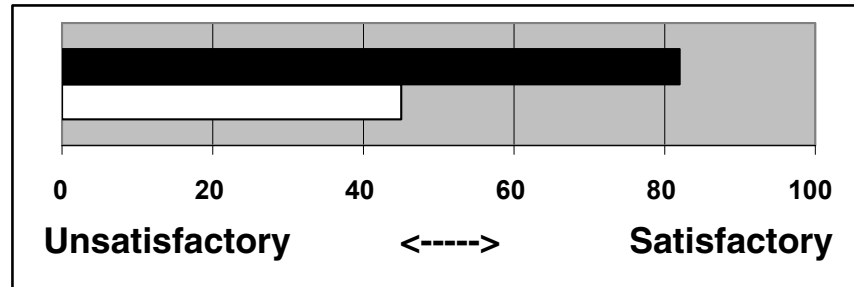
Rating of satisfaction with the dynamics of the radar altimeter symbol ($n = 6$)



Rating of use of symbology for accurately and rapidly reporting heading to target information in the tactical scenarios ($n = 6$)



Rating of vertical situation indicator readability for each symbology set ($n = 6$)



Rating of satisfaction with the dynamics of the vertical situation indicator symbol ($n = 6$)

APPENDIX F. PILOT PERFORMANCE DATA

This section contains all of the data collected during the experiment. Some data represent individual pilot performance and some charts represent averaged performance for all pilots. Data below that showed a significant result were repeated in the main body of the report and analyzed in detail.

Comanche SIM II Test Results



PERFORMANCE ANALYSES

Unusual Attitude Recovery (Color Code: **Desired**, **Adequate**, **Not Adequate**)

Performance Parameter	Compressed	Contact Analog		Significance
Roll Angle	2.60 deg	2.94 deg		no sig
Pitch Angle	3.14 deg	2.90 deg		no sig
Vertical Rate	160.64 fpm	116.90 fpm		no sig
Recovery Time	20.75 sec	19.47 sec		sig Trial effect p < .05

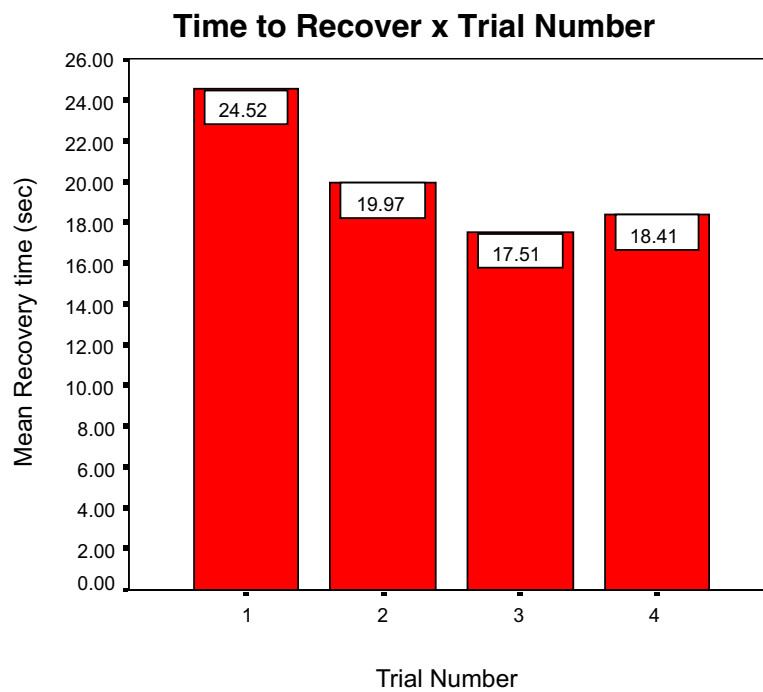
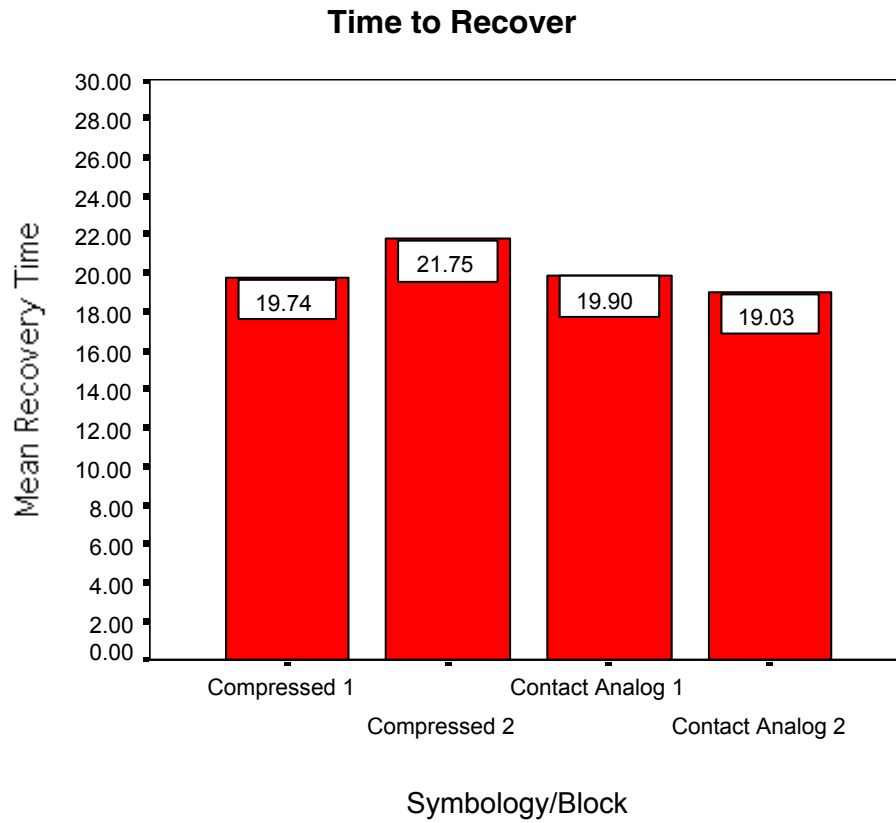
Hover Turn Bob-up (Position Hold)

Performance Parameter	Compressed	Contact Analog		Significance
Longitudinal Error	5.47 ft.	4.99 ft.		no sig
Lateral Error	4.89 ft.	6.29 ft.		sig Trial effect p < .05
Final Rad Alt Error	1.77 ft.	2.42 ft.		no sig
Heading Error	1.45 deg	1.66 deg		no sig
Time to Complete	13.35 sec	15.37 sec.		sig Symbol effect p < .01

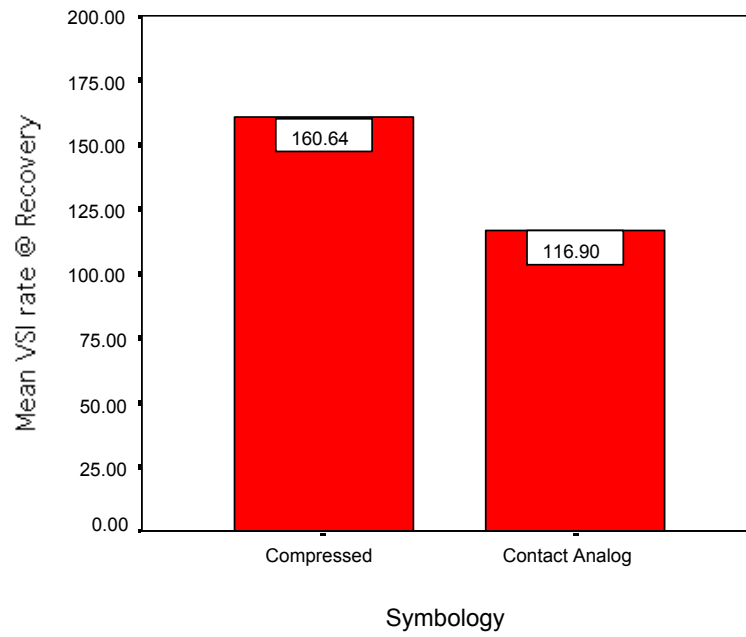
Hover Turn Bob-up (AFCS)

Performance Parameter	Compressed	Contact Analog		Significance
Longitudinal Error	28.27 ft.	37.36 ft.		no sig
Lateral Error	22.29 ft.	26.29 ft.		no sig
Final Rad Alt Error	2.80 ft.	3.91 ft.		no sig
Heading Error	2.09 deg	1.59 deg		sig Trial effect p < .05
Time to Complete	16.98 sec.	18.37 sec.		no sig

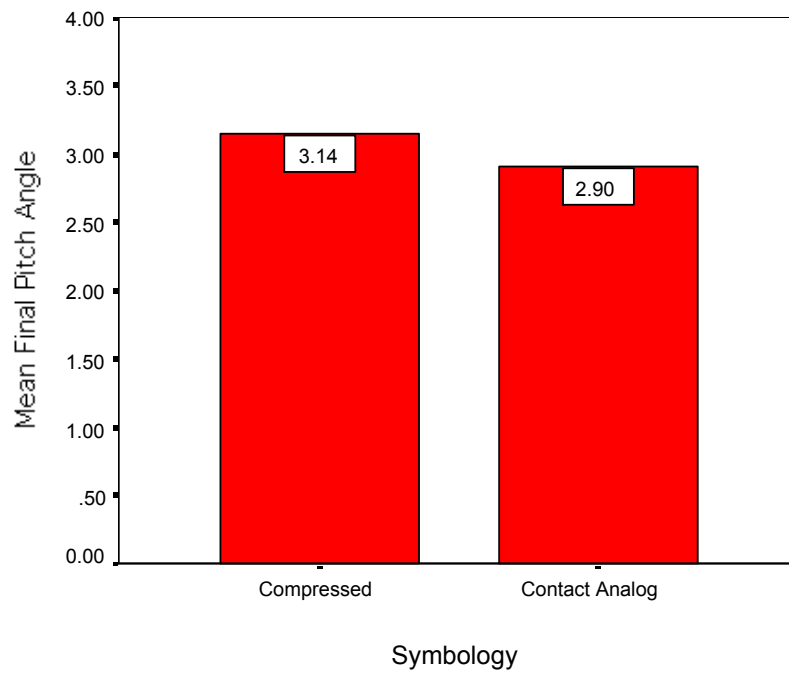
UNUSUAL ATTITUDE PERFORMANCE DATA

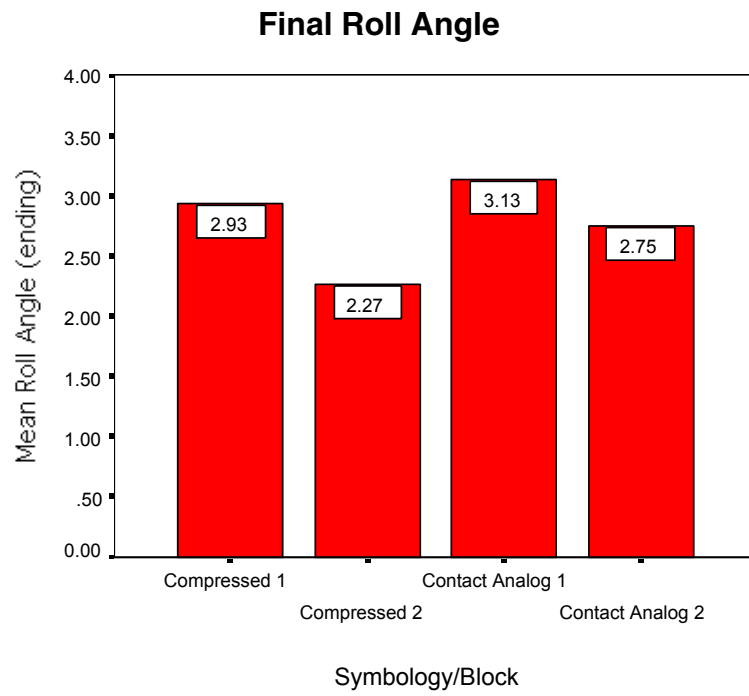


VSI Rate at Recovery

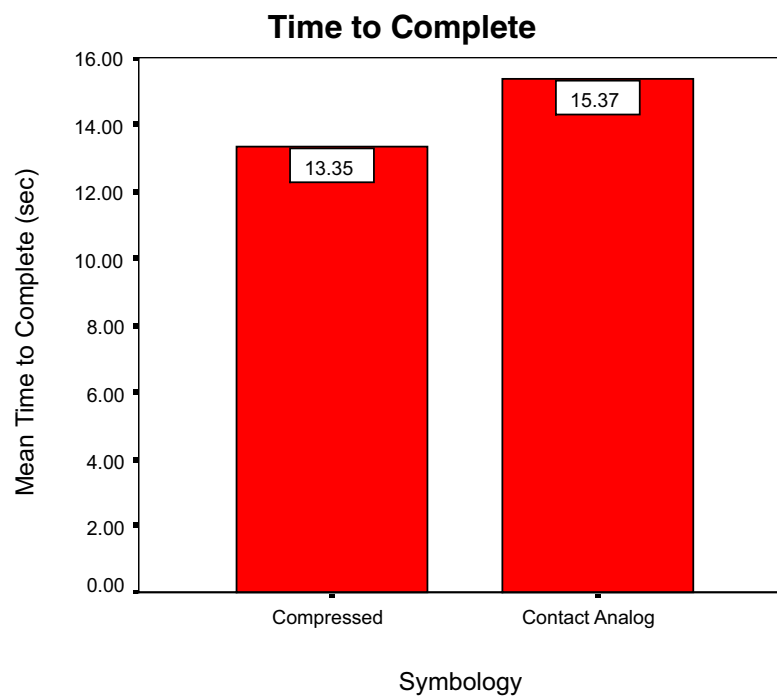
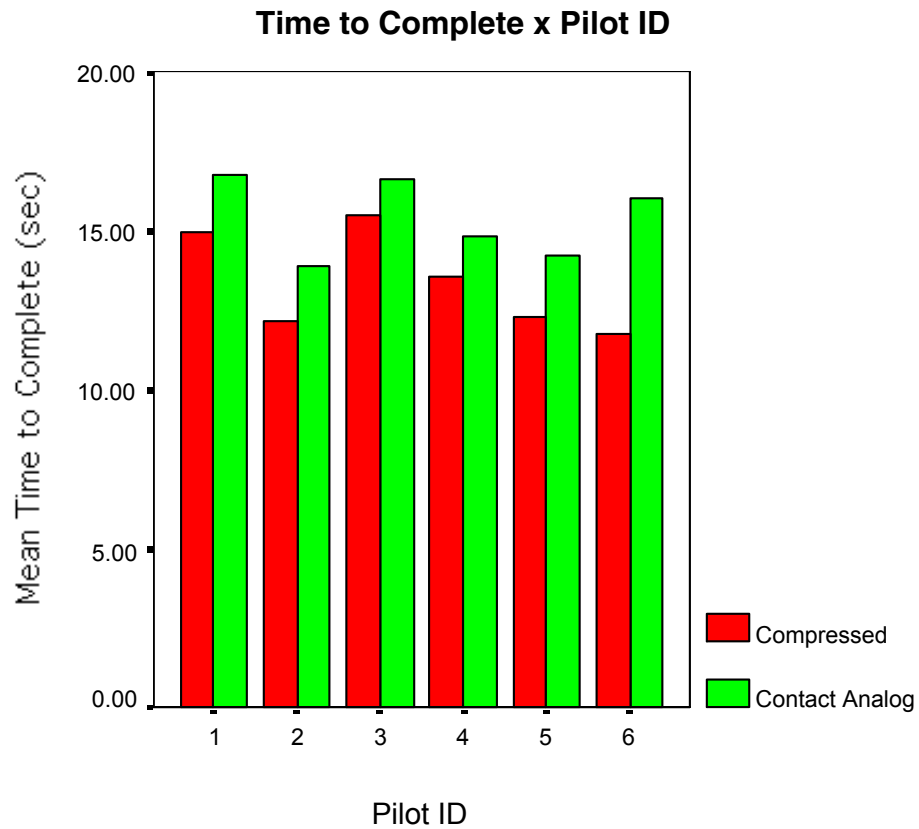


Final Pitch Angle

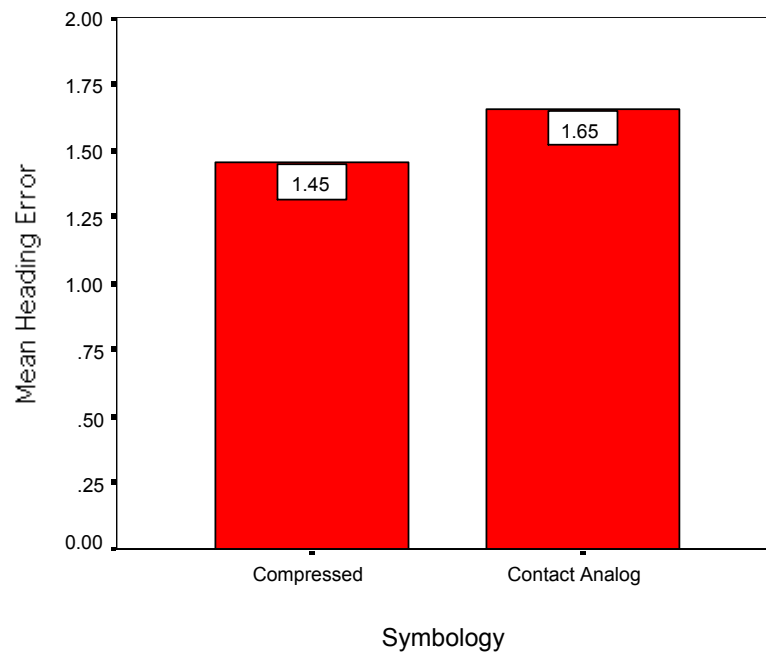




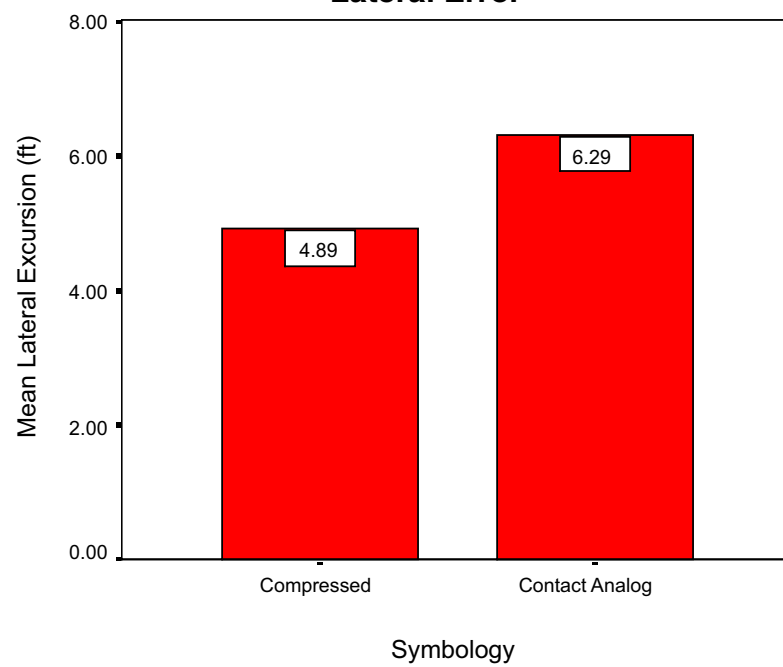
HOVER TURN BOB-UP (POSITION HOLD) PERFORMANCE DATA



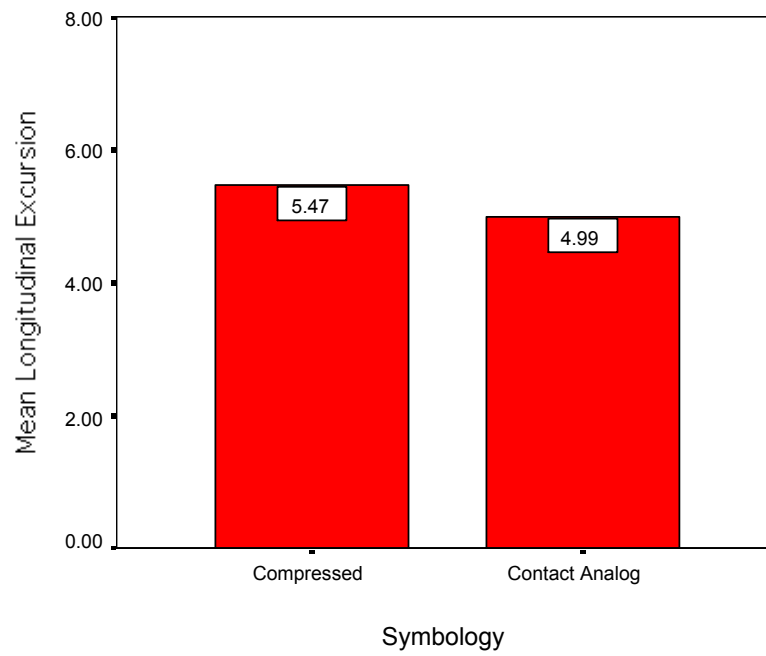
Heading Error



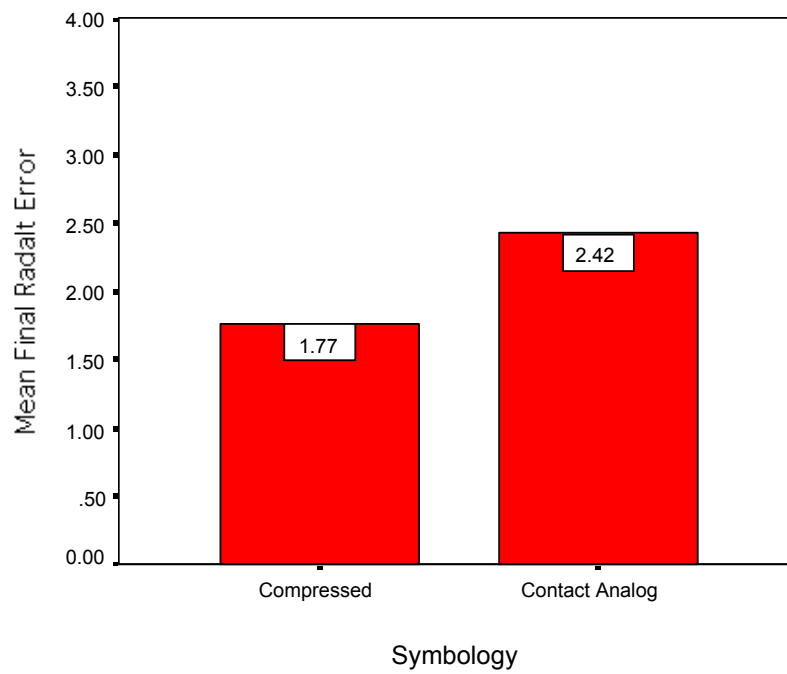
Lateral Error



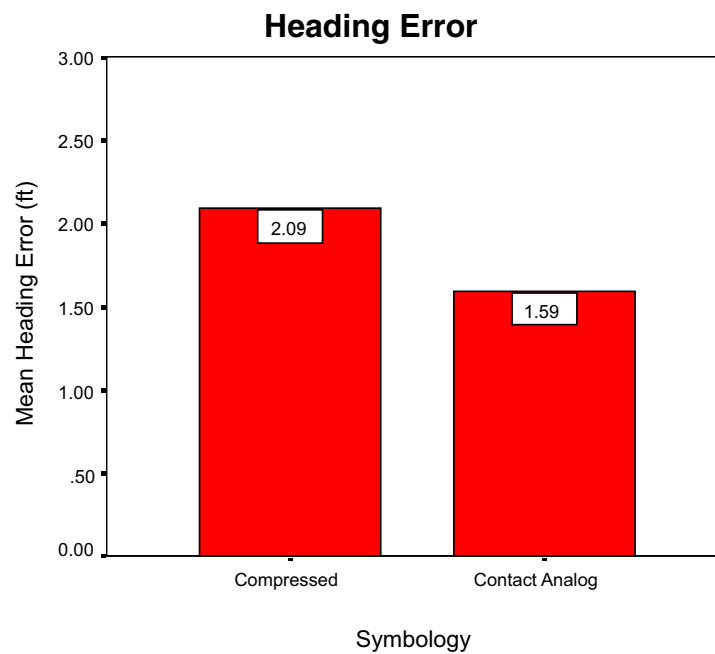
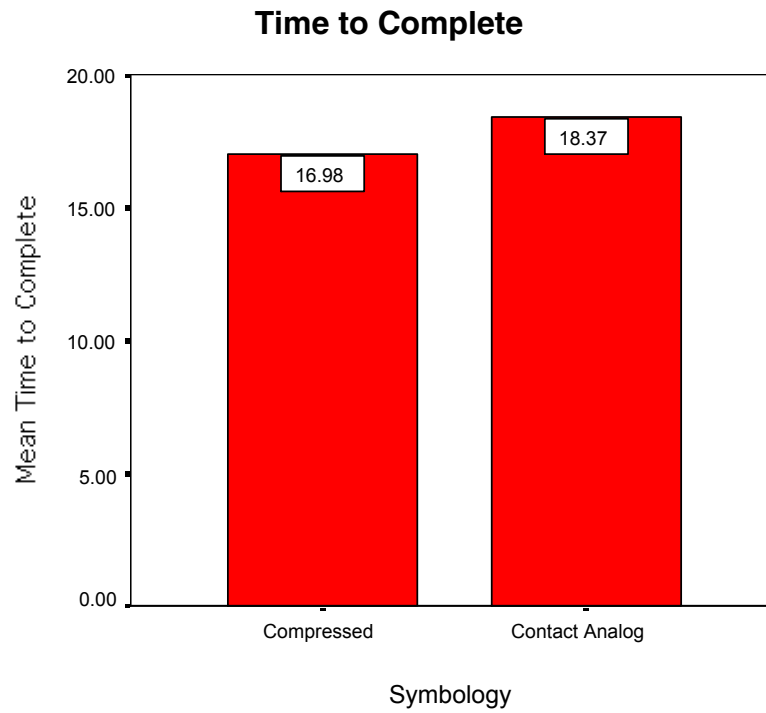
Longitudinal Error

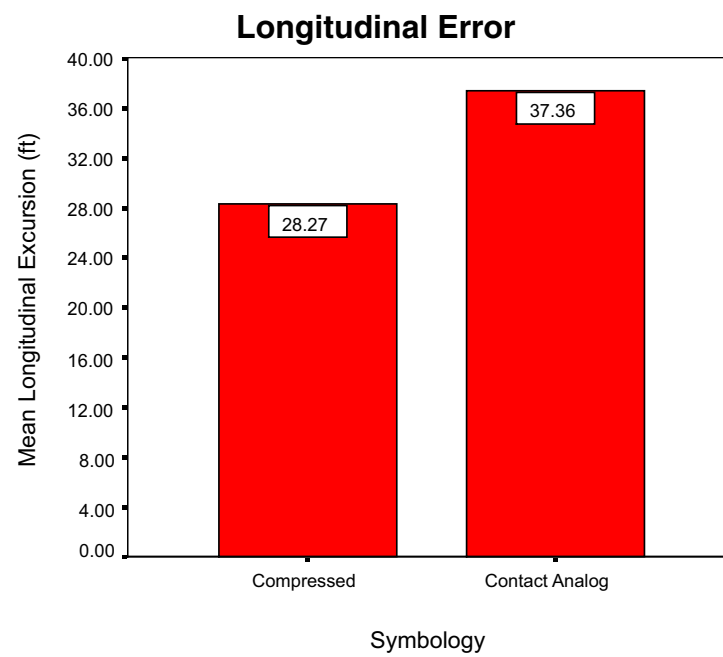
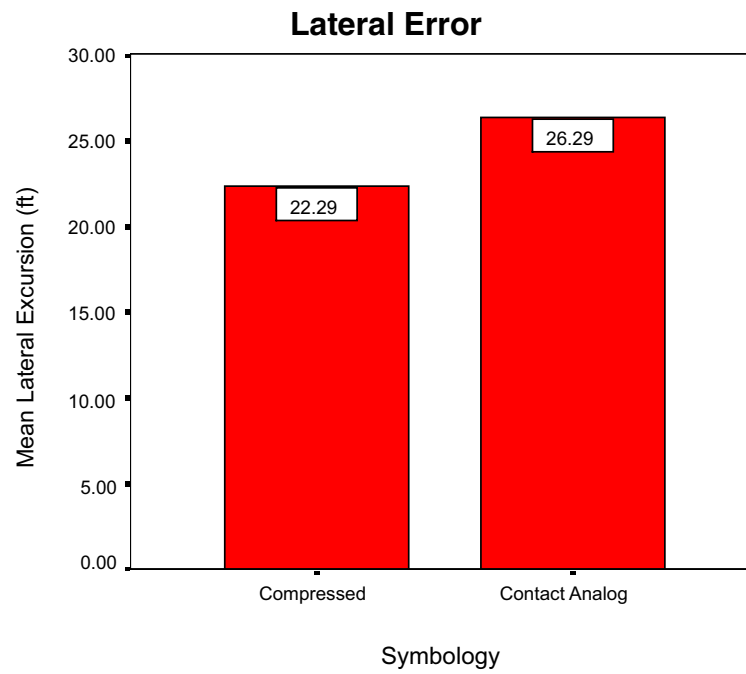


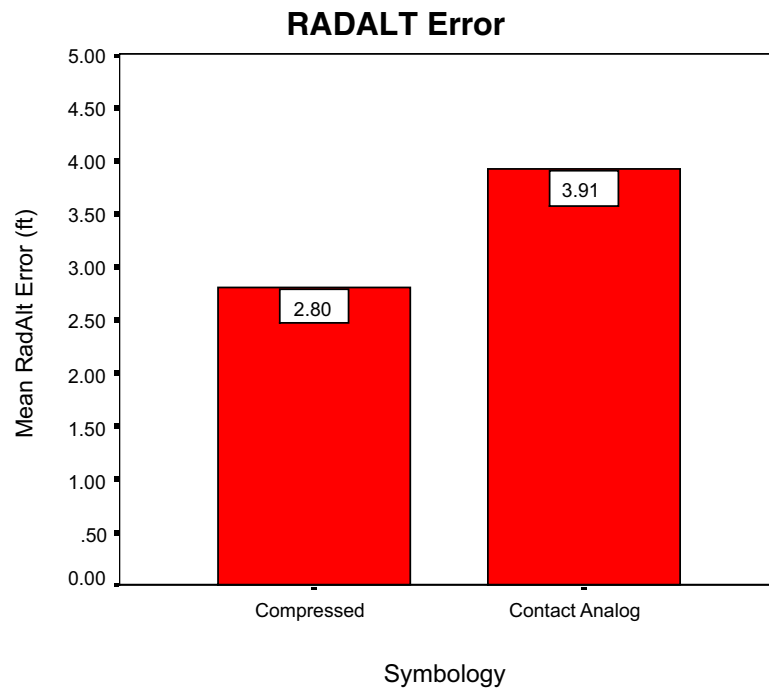
Final RADALT Error



HOVER TURN BOB-UP (AFCS) PERFORMANCE DATA

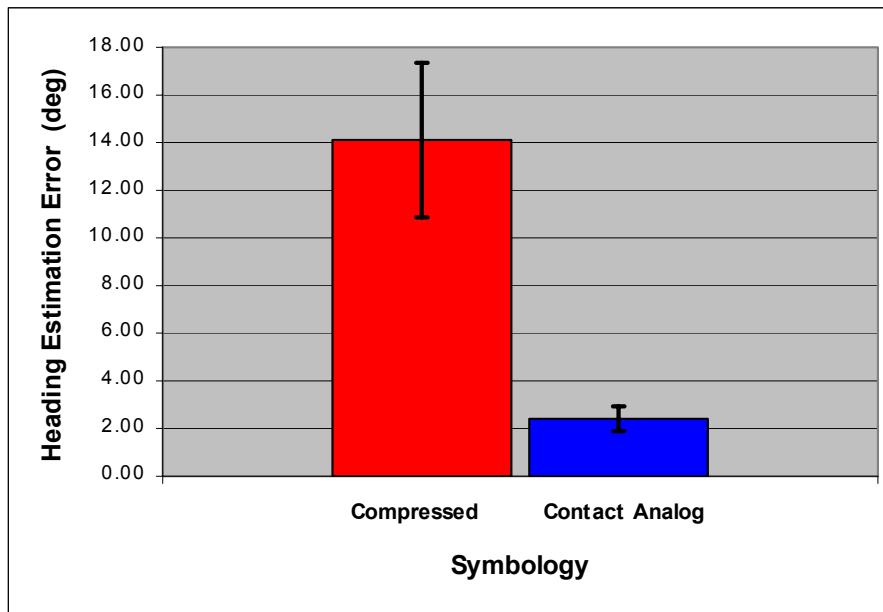




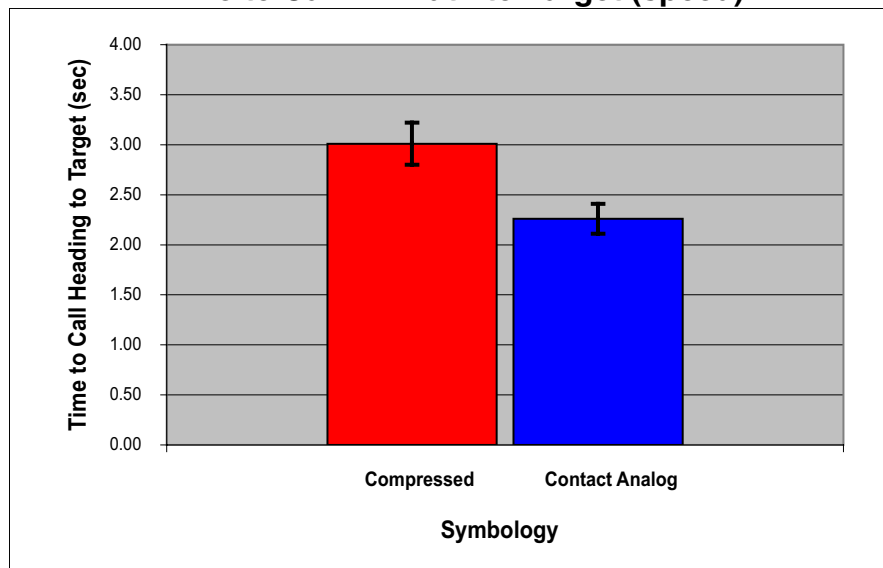


NOE MISSION PERFORMANCE DATA

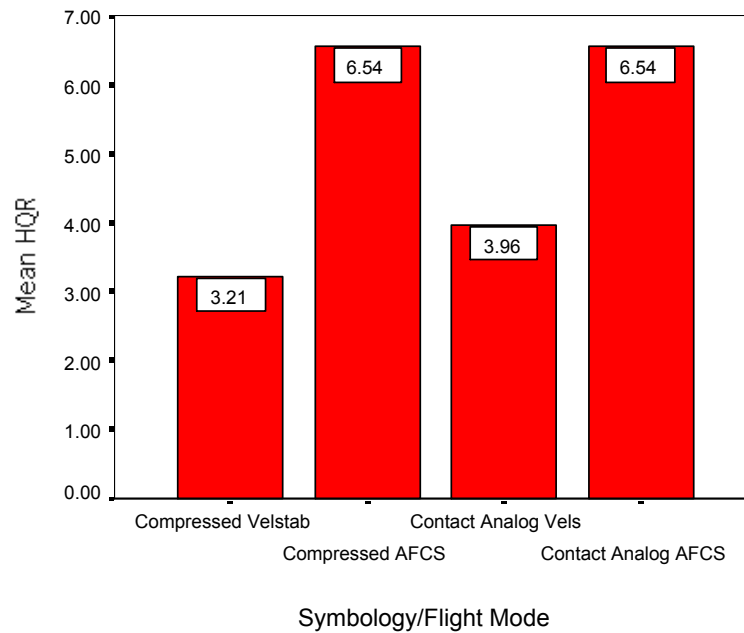
Azimuth to Target Estimation Error



Time to Call Azimuth to Target (speed)

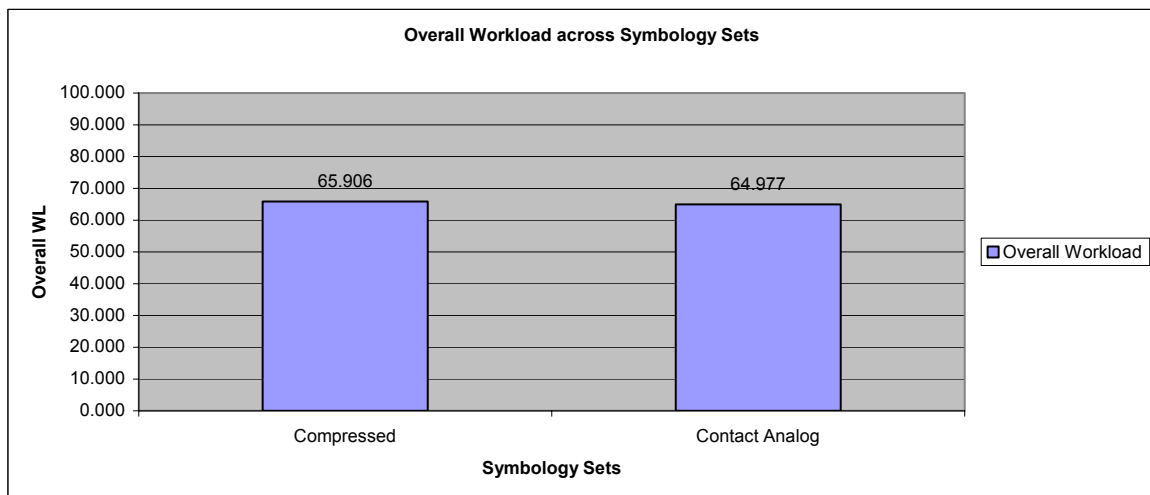


HOVER TURN BOB-UP (POSITION HOLD/AFCS) HQRS

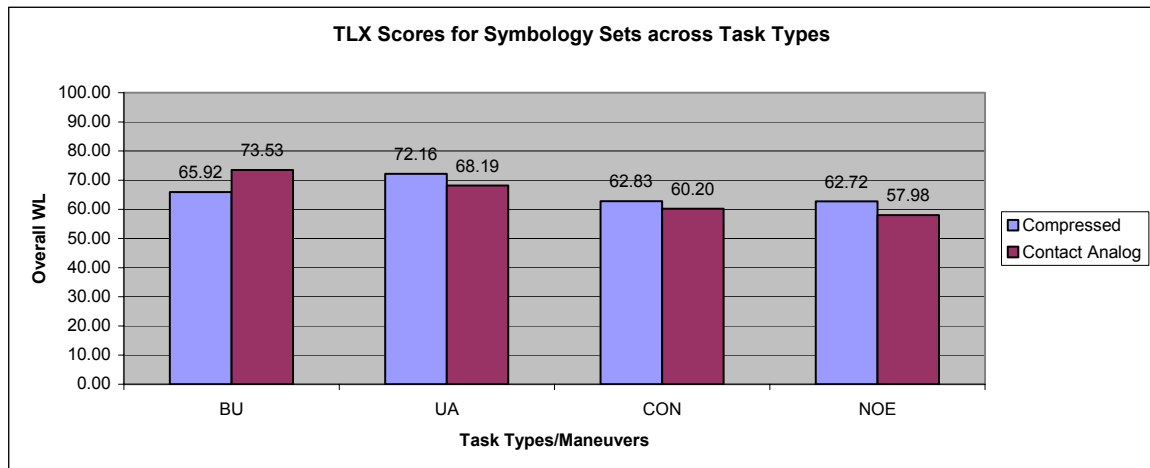


WORKLOAD AND SITUATIONAL AWARENESS RATINGS

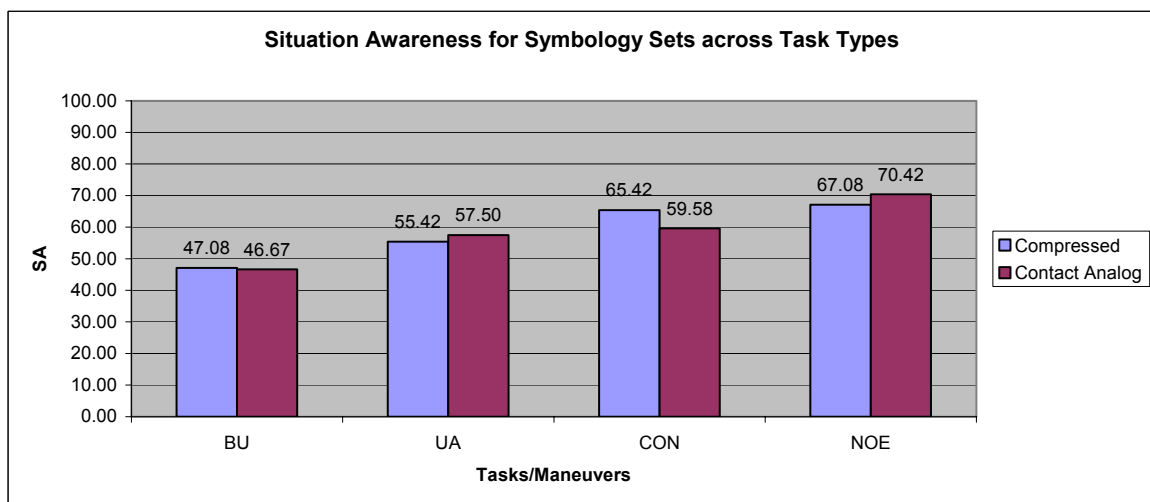
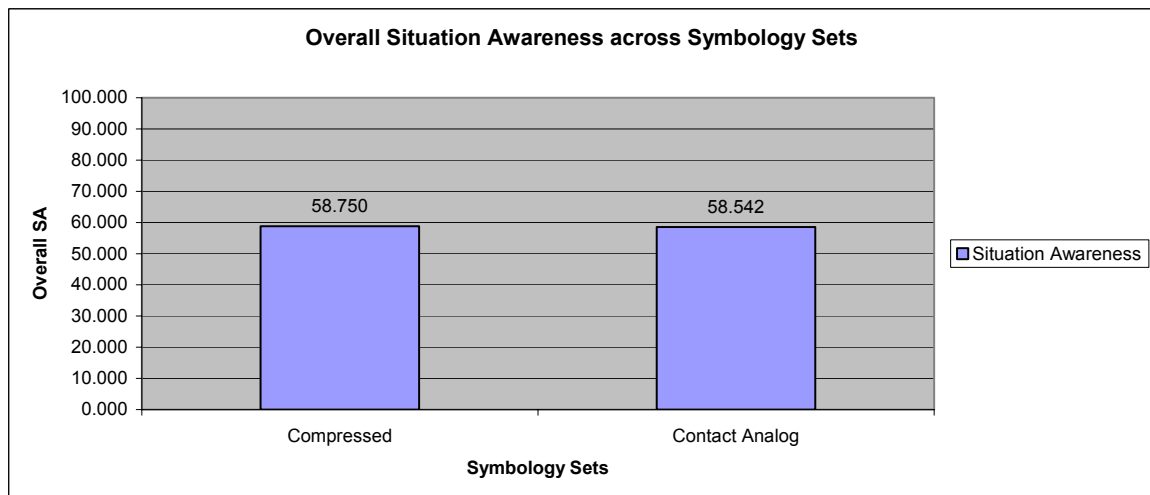
Overall Workload



NASA-TLX Scores for All Maneuvers Completed



Situational Awareness Ratings



APPENDIX G. PILOT COMMENTS

Each pilot was asked to provide an end of simulation top-level summary of their overall opinion concerning the effectiveness and usability of the two different symbology sets. Their comments are provided below. The summary comments are followed by the detailed comments that explained the HQR ratings for the hover bob-up maneuver.

Pilot 1

1. Consider having the pilot look off axis during the Unusual Attitude Recovery.
2. Fog was an excellent and realistic addition to the UA.
3. Favored the compressed heading tape for 2 reasons. First the tape was more readable if a rapid turn. Second, you could see the target heading during the entire maneuver, which reduced cross-check time and workload.
4. Contact Analog symbology is not readable during rapid turn or rapid head movements.
5. Favored the VSI tape in 1295 symbology. It seemed easier to use with the pointer against the scale. You could set the pointer on the index and use appropriate control input to keep it where you put it.
6. Liked the hybrid #2 symbol set. Would like to add the 1295 VSI tape to it.
7. If I had to choose between CA and 1295 I would choose CA.
8. The earth-referenced horizon line disappears during certain nose up or head up situations. Not having a visible horizon could present an unsafe situation.
9. The symbology seems too spread out. This increases mental workload in the cross check. Moving the symbology closer to the center of the display would reduce workload.
10. The null point on the 1295 symbology VSI is not predominant enough causing you to have to search for it.

Pilots 2 & 5

1. If you had to choose one symbology set in its entirety which did you prefer?
Pilot 5 – Hybrid #2 – Contact Analog with compressed heading tape.
Pilot 2 – 1295.
2. Did you see any safety issues with any of the symbology sets?
 - Barometric altimeter was too far to the left of the central field of view to be usable.
 - Earth referenced horizon line could not be seen during nose up or nose down pitch attitudes such as those experienced during the unusual-attitude task.

3. Were there any improvements needed to make Contact Analog symbology more usable or mission effective?
 - Move the torque symbol to the left of the radar altimeter.
 - The first 100 ft of the radar altimeter should have tic marks at 10-ft increments.
 - Moving the altitude information to the left and airspeed to the right was not a problem. Adaptation was easy.
 - Replace the Contact Analog VSI with a pointer against a scale like the 1295 presentation. Move the entire 1295 altitude group in to replace the Contact Analog.
 - Replace the torque thermometer symbol with a digital readout that is coded to show OGE hover torque as well as max continuous and max torque available.
 - The head-referenced heading tape has no known tactical value. Bearing to target information can be gotten through other means other than pointing the head and reading the scale. Recommend the compressed heading tape with a digital readout beneath the scale.
 - Would like to be able to adjust the intensity of the symbology to compensate for the variable brightness of the outside scene.

Pilots 3 & 4

Optimum Display Preferences and Justification following Comanche Heading Tape vs. 1295 Symbology Simulation

General Comments

1. I saw little need for the symbology to be spread to the edges of the display. I had difficulty focusing on images on the edges of the display in the contact analog format requiring to scan away from the central field of view especially as the task requirements were increased.
2. If symbology is moved to the edges of the display, it must be bright enough to be interpreted by the pilot without requiring scan and focus during demanding multi-axis tasks.
3. Airspeed and altitude in the form of a standard T or alternate had little impact on the workload or task performance during the simulation.
4. Unusual attitude recovery tasks were independent of symbology tasks once task performance was achieved. Desired performance was achieved using basic attitude and pitch corrections only until the acceleration ball could be driven to the center of the 5-knot hover cueing dots. IVVI indications were also very important during the tasks to control climb and descent.
5. Little difference in task performance was observed with any of the hybrid symbology sets.
6. Skid/slip ball should not appear in any symbology set unless turn coordination logic is ON.
7. A compromised set of symbology from each symbology set can mitigate safety issues and substantially improve the performance of both display sets for the maneuvers evaluated during the simulation.

8. Preferred Symbolology Set – 1295

Justification: Nearly all of the symbolology was focused on primary field of view, was easy to read and interpret, and symbolology dynamics were predictable.

Recommended Changes

- a. Add digits at the center of the heading tape to provide the pilot with the direction he is looking. The 180-deg field of view on the compressed heading tape provides a very predictable indication of the aircraft heading in a screen-fixed method. This digital indication will help the pilot with target identification in azimuth without cluttering the center of the pilot FOV.
- b. Remove the LOS indication in preference to an aircraft symbol that is implemented in the same manner as the Contact Analog Comanche symbolology. The LOS indicator only provides pitch cueing while the aircraft symbol used in the Contact Analog symbolology provides pitch cueing as well as a reference to the pilot as to the direction the aircraft nose is pointing. The location of the nose helps with sideslip control at slow speeds to help keep the tail behind the aircraft. The aircraft symbol also provides a quick reference to the pilot when he is looking over the nose. This indication is currently missing in the Apache 1295 symbolology.
- c. Add the Contact Analog current waypoint and next waypoint indications to the 1295 Apache symbolology set, but reduce their size. This symbolology is very useful and easy to interpret over the digital information provided in the Apache 1295 symbolology set. Retain the command heading indicator on the heading tape for cross reference.

Safety Issues

- a. Pilot is not always aware of the direction he is looking, which can result in spatial disorientation especially during more aggressive maneuvering. This is especially true during unusual attitudes when inner ear disorientation can result due to the head being in a different axis than the visual indications interpreted by the pilot.
- b. Pilot is not always aware of the location of the nose of the aircraft relative to the flightpath vector, which can result in poor turn coordination at low airspeed during NOE flight. This may result in tree contact or potential rollover if the pilot thinks he is landing straight ahead and the nose is not in proper alignment.
- c. Navigation indications were difficult to follow and provided poor cueing to the pilot on the visual display. The use of a moving map or hand-held map is required to provide actual identification of the waypoint location resulting in additional workload.

Contact Analog Modifications

Recommended Changes

- d. Adopt the 1295 heading tape with digital heading indicating the direction the pilot is looking. The Contact Analog heading tape is difficult to use when precision and aggressive maneuvering is required. The pilot has reduced situational awareness at high yaw rates.
- e. Remove the IVVI, barometric altitude, and radar altitude indications including the 6-sec predictor in favor of the Apache 1295 barometric altitude, radar altitude, and IVVI indications.

The 1295 indications could be made brighter and still moved to the outer edges of the display whether they are on the right or left side of the display.

- f. Remove the torque indication in favor of digital torque indication with various shadings or colorings to indicate torque limits. This indication was of limited utility and can be implemented in a smaller amount of space while providing similar clarity to the pilot. The current symbology uses critical real estate that is better used for barometric and radar altitude information rather than the very bright torque indication.
- g. Reduce the size of the waypoint markers. These were very effective for navigation and identifying the waypoint location in the scene.
- h. Adopt the screen-fixed artificial horizon line used in the 1295 symbology set. Easier to use when it remains in the primary field of view and prevents clutter at the top and bottom of the display.
- i. Vertical axis control was difficult due to the poor predictability of the 6-sec predictor and the poor dynamics positioning of the IVVI. The IVVI was too dim and too far outside the primary field of view for the pilot to use effectively at low airspeed. These issues resulted in more ground contacts with Contact Analog than with any other display method.
- j. Earth-referenced symbology can cause significant screen clutter depending on where the pilot is looking. This can result in display confusion and potential disorientation.
- k. The Earth-referenced horizon line was difficult to use with respect to unusual attitudes and could not be present in the field of view depending on where the pilot was looking. This can result in significant disorientation especially during the initial phases of an unusual attitude recovery.
- l. The significant gaps in the heading tape and the Earth-fixed implementation of the heading tape made it difficult to interpret especially at high yaw rates or while trying to manage a multi-axis task. This increase in workload in conjunction with poor vertical cueing can significantly impact pilot performance during low, moderate, and especially high-gain multi-axis tasks.

Pilot 6

- 1. In order to evaluate the hybrids more fully you need to incorporate NOE and contour maneuvers into the evaluation.
- 2. Training locally was adequate when combined with the 7 hrs of CPC time prior to coming to Ames. Without the CPC time there would need to be more simulation hours allotted for training.
- 3. Which symbology set would you choose if you had to choose one without modifying it? Answer: Would choose 1295 over Contact Analog.
- 4. Were there any safety issues noted with any of the symbology sets?
 - The variable radar altimeter scaling may cause inadvertent ground impact due to vertical rate buildup.
- 5. Were there any design changes that you could recommend for Contact Analog symbology?
 - Recommend the radar altimeter have 10-ft tic mark scaling up to 100-ft AGL.
 - Recommend the symbology be moved in toward the central FOV. The current design is too spread out, which increases workload and slows the cross check.

- Switching altitude information to the right side and moving airspeed to the left was not an issue and seemed to make sense with respect to which hand controls what axis.
- During the unusual attitude, when the airspeed increased to > 20 kts, the trim ball appeared and it was mistaken for the acceleration cue.

6. Wrist coupling was unavoidable while trying to maintain hover position with the SAC.

If you could design a symbology set for the maneuvers in this test what would it look like?

- Compressed heading tape
- Indexed VSI with 1295 style pointer against a fixed scale
- Linear radar altitude scale with multiple regions more like the 1295 scale
- Contact Analog torque scale as designed (digital readout with ring and index marks)
- Contact Analog hover cue symbology
- Move the symbology in closer to the central FOV
- Delete the 18° gap in the horizon line. Make the gap fit the iron wings
- Need a selectable pitch ladder for up-and-away flight
- Display a hover position reference
- Display an analog airspeed indicator
- Put a filter on the radar altimeter 6-sec predictor to make it more usable. The filter should act much like the Hybrid 3 predictor.

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